BASIS FOR THE DEVELOPMENT OF A SOIL STABILIZATION INDEX SYSTEM

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A soil stabilization index system has been developed to aid military engineers in selecting the appropriate type and amount of soil stabilizer to use in pavement construction. This report contains the index system and the basis for its development. The index system is entered with easily determined soil properties and flow charts are followed to arrive at the most suitable stabilizer. Subsystems containing appropriate tests are used to determine specific amounts of stabilizers. Use factors, construction factors, and environmental factors are also considered in the decision-making process. Although the index system was based on a comprehensive review of published information and personal opinions of acknowledged experts in the soil stabilization field, there were often conflicting viewpoints necessitating validation of the proposed system. A plan for laboratory validation of the index system is outlined.

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14 KEY WORDS	LINK A		LINK B		LINK C	
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Pavements						

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FOREWORD

This report was prepared by the Texas A&M University, College Station, Texas, under Contract F29601-70-C-0008. The research was performed under Program Element 63723F, Project 683M, Task 4.9.001.

Inclusive dates of research were November 1969 through December 1970. The report was submitted 26 November 1971 by the Air Force Weapons Laboratory Project Officer, Captain Phil V. Compton (DEZ). The previous project officer was Captain David D. Currin (DEZ).

This technical report has been reviewed and is approved.

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SECTION I

INTRODUCTION

1. Background

The United States Air Force currently owns over 500 million square yards of pavement. Runways, taxiways and parking aprons alone have a total surface area equivalent to a 200 foot wide runway stretching from the state of Washington to the southern tip of Florida.

These pavements represent nearly 40 percent of all funds spent for support facilities, and nearly 400 million dollars are spent annually in maintaining these facilities. This figure would be significantly increased if it included pavements owned by other branches of the United States armed forces.

To effectively cope with this substantial pavement inventory, military engineers involved in maintaining, strengthening and reconstructing existing pavements, as well as those constructing new pavements, must be aware of any and all construction alternatives available to reduce construction time, initial cost and maintenance costs. The attractive engineering and economic benefits of soil stabilization make it important that this alternative be considered.

Stabilizing soils to improve their engineering properties is not new - it has been practiced for centuries. However, chemical soil stabilization did not gain widespread acceptance in road and runway construction until after World War II. With increasing use of stabilization processes during

the last 2 1/2 decades, voluminous research results have been published by highway departments, groups representing producers of stabilizing materials, and various research organizations, to name a few.

Even though a wealth of technical information and data now exists on soil stabilization, there has been no significant attempt to correlate this information into a useable system which would classify or index soils with respect to a) their suitability for stabilization, and b) the most appropriate type and amount of stabilizer to use. To further complicate matters the available data often favor a particular product, and do not include the worldwide variety of soils which military engineers are likely to encounter. This creates a dilemma for the military engineer, who often lacks extensive training in soil stabilization, who lacks time and equipment for sophisticated evaluation tests, and who often works in areas where there are no previous records regarding feasibility of soil stabilization.

To alleviate this problem, the U. S. Air Force Weapons Laboratory (AFWL) has embarked on an extensive research program covering many aspects of soil stabilization. Initial research involved the determination of the basic physico-chemical properties of soils which influence their response to stabilization. Next, the Air Force sponsored a research project at Texas A&M University aimed at developing a soil stabilization index system. The ultimate objective of the index system is to determine a soil's suitability for stabilization and to indicate the most appropriate type and amount of stabilizer. The index system should contain all useful knowledge on soil stabilization arranged in such a form that it can be effectively used even by engineers who are not trained in stabilization techniques. Of necessity, the stabilization index system should not only consider those relevant soil properties that influence soil stabilization, but should also take into

account such factors as:

a. urgency of construction

b. location of the stabilized layer in the pavement

c. type of construction equipment available or needed

d. influence of the environment on the stabilized layer

2. Scope of Report

It was specified that the soil stabilization index system be developed in two consecutive phases: Phase I was to be the establishment of the index system based on existing knowledge; Phase II was to be devoted to filling in the voids in knowledge and validating the index system by appropriate testing.

This report is concerned primarily with Phase I of the research. In particular, this report contains the index system and detailed justification for the establishment of the system. It is not intended as a complete text or manual, although, by the use of appropriate appendices, it may serve as such.

During the accomplishment of Phase I of the research, many gaps in knowledge were identified which will reduce the reliability of the index system for use in the field. In this report the more critical gaps have been identified for study in Phase II of the research program. In addition, a test program for validation of the index system is outlined.

Finally, several comments and recommendations are made pertaining to the overall Air Force soil stabilization program. For the most part, this information was also uncovered during accomplishment of Phase I.

SECTION II

THE AIR FORCE STABILIZATION SYSTEM

1. Objectives

One of the Air Force objectives is to develop a systematic approach to soil stabilization. When stabilization is used in a structural element of a road or runway, it then encompasses the larger overall problem of pavement design. It is not within the scope of this project to consider the pavement design problem as such. However, a brief discussion of how stabilization interacts with pavement design is warranted.

An engineer faced with designing a pavement must first assess the load-carrying capacity of the existing subgrade. The Air Force presently specifies the CBR method of strength determination and uses this as a design method also. Depending on the subgrade CBR, it can be determined how much overlying material of higher quality must be used based on the type of traffic anticipated and the life of the facility. This is basically a structural design problem, but there may be other overriding factors - such as frost penetration - that will influence the thickness of overlying material.

At this point the engineer may consider stabilization. Whether to stabilize the subgrade, the overlying material, or both, is a decision which must be made. The military engineer must base his decision on many factors including economy, availability of stabilizer and speed of construction. It is here that the index system should assist the engineer. He should be able to use the index system as a guide to tell him what kind of stabilization to

use and how much stabilizer he should use. Certain soils are not amenable to stabilization and the index system should be capable of relaying this information to the engineer. Other circumstances, e.g., climatic conditions, lack of appropriate equipment, etc., may also rule out the possibility of stabilization. Again, the index system should provide this information. However, the engineer should not be under the illusion that the index system, in its present state of development, will provide design curves or other information of a structural design nature.

It is of utmost importance for the engineer to realize that the index system is not a substitute for proper pavement design and that stabilization is not a panacea for all pavement problems.

2. Processes of Soil Stabilization

Stabilization has been defined by Lambe (1)* as "the alteration of any property of a soil to improve its engineering performance."

In recent years, the term *modified* has been used to indicate that general soil properties have been improved without appreciable gains in strength, whereas, stabilized has been reserved for cases where definite strength gains are apparent. Although the term, modified, has not been universally accepted (some engineers consider that an improvement in any characteristic, not necessarily strength, constitutes stabilization), nevertheless, it is a convenient definition to use and will be adopted in this report.

The primary stabilization methods are:

a. chemical stabilization

b. mechanical stabilization

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*Numbers in parenthesis refer to References.

Chemical stabilization, as the name implies, is the use of certain chemical additives which are mixed into the soil to change the surface molecular properties of the soil grains and, in some cases, to cement the grains together resulting in strength increases.

By far the largest volume of chemical stabilizers used throughout the world are lime, cement and bitumens. Many other additives have been used, some by themselves and some in conjunction with the three major ones listed above. However, none of the many other stabilizers available have gained universal acceptance and significant background information on their applicability is lacking. Thus, the index system at present will be concerned only with the three major stabilizers, i.e., lime, cement and bitumens.

Mechanical stabilization may be accomplished by:

a. changing the gradation of the soil by the addition or removal of particles

b. densifying or compacting the soil

Soil compaction represents one of the most economical methods of stabilization. In addition to its separate use, proper compaction is also required with soils which have been chemically stabilized.

3. Air Force Soil Stabilization System

The overall systematic approach to the Air Force Soil Stabilization Index System is shown in Figure 1. The development of this general scheme is discussed below.

a. Type of Stabilization

When stabilization is to be used, it is then necessary to decide whether mechanical stabilization alone will suffice, or whether it will be necessary to utilize chemical stabilization. In addition to the

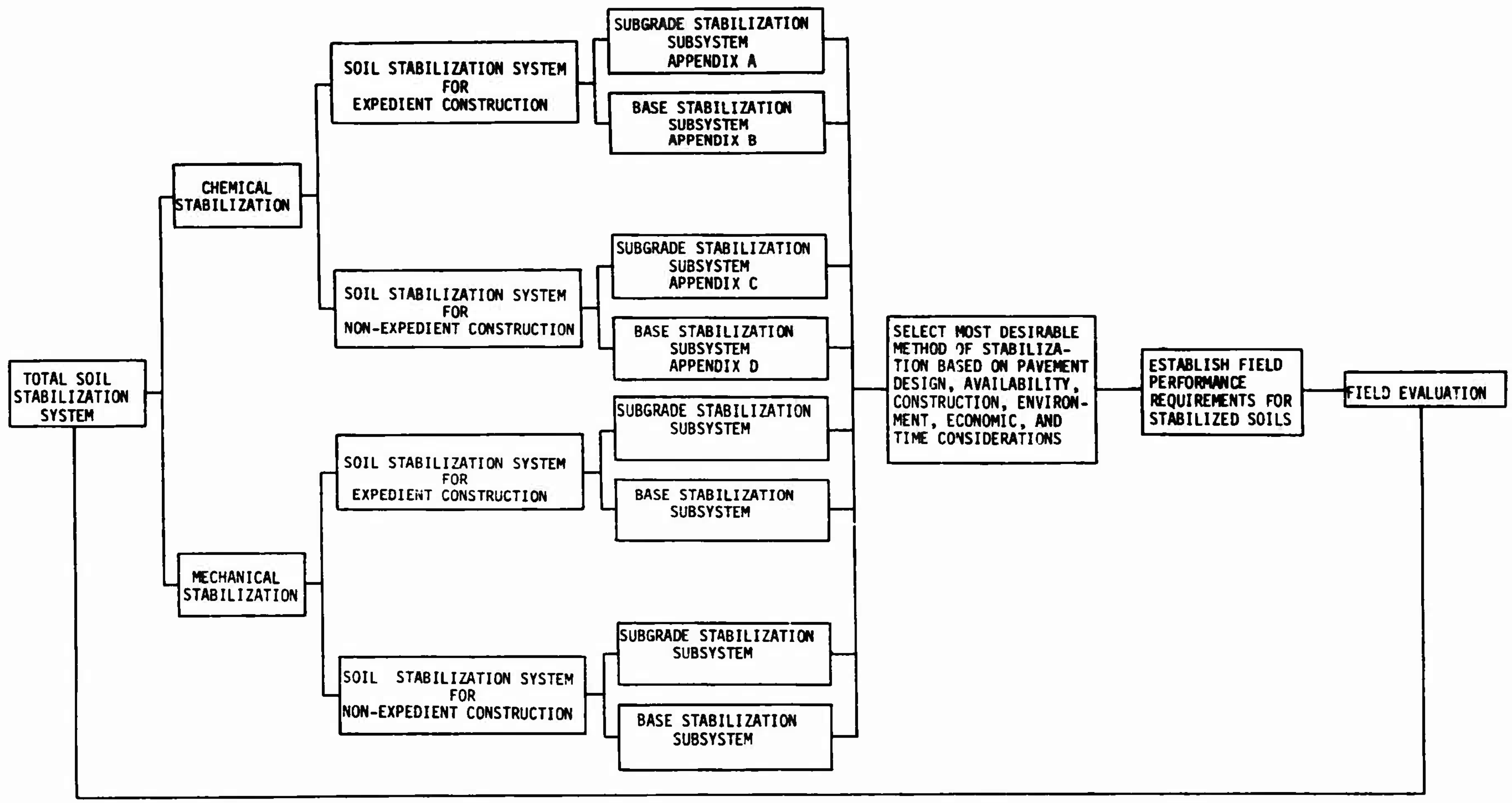

FIGURE 1. THE AIR FORCE SOIL STABILIZATION SYSTEM

pavement design aspects which must be considered, the engineer must often weigh the economic gain obtained by mechanical stabilization against that obtained by the addition of chemicals. From the military aspect, time of construction may well override all other factors and could be the sole reason for choosing one stabilization method over another.

b. Use Factors

To be of most benefit, the index system should recognize the two significantly different uses for which it may be applied, i.e., Zone of Interior construction and Theater of Operations construction. More importantly, under the present mobility concept of the Air Force, it should be particularly suitable for hasty, forward airfield construction. For this reason, the index system was divided into two construction categories as follows (refer to Figure 1):

1. Expedient construction
2. Nonexpedient construction

Expedient is considered to be a short life, high risk situation in which a limited construction and materials testing capability exists, and time is of the essence. Nonexpedient is considered to be all other situations. The tests used for establishing type and amount of stabilizer used in expedient operations are the rapid, unsophisticated type, whereas the more conventional tests are utilized in nonexpedient construction.

In certain nonexpedient, permanent construction situations (such as might occur in the Zone of Interior) there is usually an unlimited testing capability. Then, it may be desirable to consider chemical stabilizers other than those presently considered in the index system and conduct a more thorough laboratory evaluation. In such a situation,

the index system will provide a starting point for the investigation.

Figure 1 shows another way in which use factors are entered into the index system by specifying different subsystems for subgrade and base course stabilization. Subbases are not considered, but they may fall either in the subgrade or base course subsystems depending on the material type and desired strength characteristics.

It should be noted that the index system is presently limited to stabilization for structural elements of roads and runways. It does not include, for example, use of dust palliatives, erosion control, etc.

c. Basic Soil Parameters

These are the soil properties that influence the response of the soil to stabilization. They are not shown directly on Figure 1, but they enter into each of the subsystems which are discussed later. Undoubtedly, all of the parameters that influence stabilization are not included and, in fact, they may never be known.* However, those included are considered to be the most important with the present state of knowledge and are among the easier parameters to obtain. They are:

1. Gradation, particularly the percent finer than 0.074 mm (#200 sieve), 0.05 mm and 0.005 mm
2. Plasticity index
3. pH
4. Sulfate content
5. Organic content

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*The work referred to in Section I regarding basic physico-chemical properties was not completed at the time this report was written. Preliminary indications are that most of them are included in one form or another.

Other important parameters are expected to be forthcoming, and they will be incorporated into the index system as seen fit.

d. Environmental Factors

These are factors that might influence the ultimate suitability and durability of the stabilized soil. Again, they are not shown directly in Figure 1, but are included in the various subsystems. They are based primarily on climatological effects and not on the total environment (which might also include such factors as wheel load and number of repetitions). Both rainfall and temperature must be considered since either can significantly influence the type and amount of stabilizer used.

e. Construction Factors

Military engineers faced with hasty construction in the Theater of Operations usually are faced with limited equipment also. Knowledge of the type of equipment required for a certain stabilization task may prove to be a valuable planning tool, not only in anticipating the type of equipment necessary to perform a stabilization task, but also in eliminating the use of a particular stabilizer if adequate equipment and time are not available.

f. Pavement Design

As discussed earlier, an important aspect of soil stabilization involves the design of the pavement cross section using stabilized materials. Under the present CBR design scheme, this is a fairly straightforward process if mechanical stabilization is used, there being no change in the basic design process. However, if chemical stabilization is used, the problem becomes more complex. Not only do the various use factors, environmental factors and construction factors

enter into play, but there is also the problem of evaluating the physical characteristics of the stabilized material. Thus, there is a continual interchange between pavement design and the total soil stabilization index system.

g. Field Performance Requirements for Stabilized Soils

The desired performance of the stabilized soils must be established by the Air Force. In most cases, this will be developed based on anticipated life of the structure and allowable time for construction. Examples of this information include the recently developed mobility concepts and various other operational requirements which have been developed by the Air Force.

h. Field Evaluation

The verification of the index system for soil stabilization must ultimately come from the user, i.e., the Air Force and its military partners. On pavement projects where stabilization has been used, adequate construction records and follow-up evaluations will be absolutely necessary to verify the adequacy of the stabilized sections. Continual evaluations of stabilized sections which are already in place (such as the work being done by the Corps of Engineers at the Waterways Experiment Station) will also aid in evaluating the ultimate performance of the index system.

The remainder of this report is devoted to the development and justification of the soil stabilization index system. Greatest emphasis is placed on development of systems and subsystems for chemical stabilization, since it is here that the greatest confusion exists. Detailed systems and subsystems for mechanical stabilization, which, in reality, represent the

more common approach to the problem, are not presented. However, the information necessary to make an engineering judgment as to whether chemical or mechanical stabilization should be used is presented, and guidelines to insure the success of a mechanical stabilization program are also presented in the appropriate places in the report. It is anticipated that eventually it will be possible to provide subsystems for the full range of mechanical stabilization procedures.

SECTION III

SELECTION OF CRITERIA FOR THE BASIS OF THE CHEMICAL SOIL STABILIZATION INDEX SYSTEM

1. Introduction

This section of the report will present criteria for the basis of the chemical soil stabilization system whereas Section VII will present criteria for the mechanical stabilization system. Criteria will be reviewed which define the particular types of soils which will most readily be stabilized by each stabilizer (lime, cement and bituminous materials), and further, will allow the engineer to determine the amount of stabilizer that is required to provide the specified improvement.

Several general guides have been published which assist the engineer in the proper selection of a stabilizer for a particular soil. For example, Air Force Manual AFM 88-51 (2) contains information which suggests that lime is a more appropriate stabilizer for highly plastic clay soils while asphalt should be used only for the coarse and fine granular soils (Table 1). More detailed guides such as those published by the Air Force (Table 2) and by Johnson (3) suggest stabilization methods for particular soil types based on both their location in the pavement structure and the purpose or function of their use (load carrying characteristics, waterproofing, etc.). Although these guides do not quantitatively indicate soil types for particular stabilizers, they do indicate the importance of recognizing the purpose of the use of the stabilizer in a particular location within the pavement

TABLE 1

MOST EFFECTIVE STABILIZATION METHODS

FOR USE WITH DIFFERENT SOIL TYPES

Soil Type	Most Effective Stabilization Methods
1. Coarse granular soils	Mechanical blending, soil-asphalt, soil-cement, lime-flyash
2. Fine granular soils	Mechanical blending, portland cement stabilization, lime-flyash, soil-asphalt, chlorides
3. Clays of low plasticity	Compaction, portland cement stabilization, chemical waterproofers, lime modification
4. Clays of high plasticity	Lime stabilization

[after U. S. Air Force (2)]

TABLE 2

SOIL TYPES AND STABILIZATION METHODS

WHICH APPEAR BEST SUITED FOR SPECIFIC APPLICATIONS

Purpose	Soil Type	Recommended Stabilization Methods
1. Subgrade Stabilization		
A. Improved load carrying and stress distributing characteristics	Coarse granular	SA, SC, MB, C
	Fine granular	SA, SC, MB, C
	Clays of low PI	C, SC, CMS, LMS, SL
	Clays of high PI	SL, LMS
B. Reduce Frost susceptibility	Fine granular	CMS, SA, SC, LF
	Clays of low PI	CMS, SC, SL, CW, LMS
C. Waterproofing and improved runoff	Clays of low PI	CMS, SA, CW, LMS, SL
D. Control of shrinkage and swell	Clays of low PI	CMS, SC, CW, C, LMS, SL
	Clays of high PI	SL
E. Reduce resiliency	Clays of high PI	SL, LMS
	Elastic silts and clays	SC, CMS
2. Base Course Stabilization		
A. Improvement of sub-standard materials	Fine granular	SC, SA, LF, MB
	Clays of low PI	SC, SL
B. Improved load carrying and stress distributing characteristics	Coarse granular	SA, SC, MB, LF
	Fine granular	SC, SA, LF, MB
C. Reduction of pumping	Fine granular	SC, SA, LF, MB, membranes
3. Shoulders (unsurfaced)		
A. Improved load carrying ability	All soils	See Section 1A above, Also MB
B. Improved durability	All soils	See section 1A above
C. Waterproofing and improved runoff	Plastic soils	CMS, SL, CW, LMS
D. Control of shrinkage and swell	Plastic soils	See section 1E above
4. Dust Palliative	Fine granular	CMS, CL, SA, oil or bituminous surface spray
	Plastic soils	CL, CMS, SL, LMS
5. Ditch Lining	Fine granular	PSC, CS, SA
	Plastic soils	PSC, CS
6. Patching and Reconstruction	Granular soils	SC, SA, LF, MB

KEY:

C	Compaction	CW	Chemical Waterproofers	PSC	Plastic Soil Cement
CMS	Cement Modified Soil	LF	Lime Flyash	SA	Soil Asphalt
CL	Chlorides	LMS	Lime Modified Soil	SC	Soil Cement
CS	Chemical Solidifiers	MB	Mechanical Blending	SL	Soil Lime

[after U. S. Air Force (2)]

structure.

Since general guides to soil stabilization have indicated that both the purpose and the location in the pavement structure are important criteria for a soil stabilization index system, and since the Air Force desires an index system for both expedient and nonexpedient facilities, several appropriate systems will be developed. The first system will be developed to satisfy the Air Force requirement for expedient construction while the second, the nonexpedient system, will be developed for use where laboratory equipment and sufficient time are available for a more detailed analysis of the soil-stabilizer mixture. The major subsystems of the soil stabilization system as described previously are shown in Figure 1. As noted in this figure, a further separation of subgrade and base course has been included for both the expedient and nonexpedient soil stabilization systems.

2. Existing Guides for Selecting Stabilizing Agents

A gradation triangle, Figure 2, is being utilized by the Army and Air Force (4) to assist the engineer in the proper selection of stabilizers. This method makes use of the following soil index properties to determine the proper type of stabilizer:

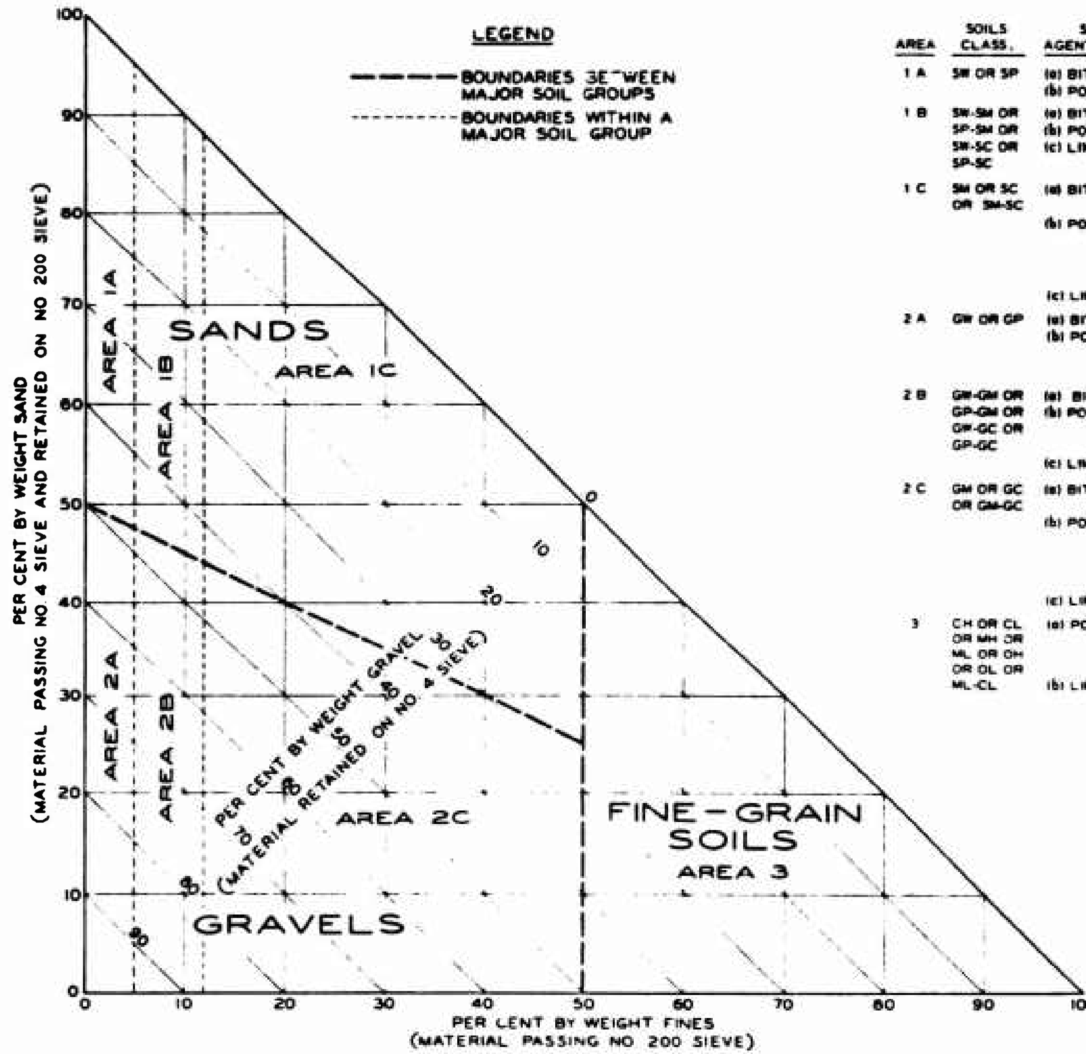
a. percent material retained on No. 4 sieve

b. percent material passing No. 200 sieve

c. percent material passing No. 4 sieve and retained on No. 200 sieve

d. Atterberg limits

As noted, the gradation triangle allows soils to be separated into selected areas. The Unified Soil Classification System is then used to further classify the soil, and appropriate Atterberg limit and gradation restrictions are applied for the particular stabilizers.



AREA	SOILS CLASS.	TYPE STABILIZING AGENT RECOMMENDED	RESTRICTION ON LL, PL & PI OF SOIL	RESTRICTION ON (-200 MATL)	REMARKS
1 A	SW OR SP	(a) BITUMINOUS (b) PORTLAND CEMENT			See note (A).
1 B	SW-SM OR SP-SM OR SW-SC OR SP-SC	(a) BITUMINOUS (b) PORTLAND CEMENT (c) LIME	PI NOT TO EXCEED 10 PI NOT TO EXCEED 30 PI NOT LESS THAN 12		
1 C	SM OR SC OR SM-SC	(a) BITUMINOUS	PI NOT TO EXCEED 10	NOT TO EXCEED 30% BY WT	
		(b) PORTLAND CEMENT	PI NOT TO EXCEED NO. IND. BY EQ: $20 + \frac{50 - \text{FINES CONT.}}{4}$		
		(c) LIME	PI NOT LESS THAN 12		
2 A	GW OR GP	(a) BITUMINOUS (b) PORTLAND CEMENT			WELL-GRADED MATL ONLY MATL SHOULD CONTAIN AT LEAST 45% BY WT OF MATL PASSING NO. 4 SIEVE
2 B	GW-GM OR GP-GM OR GW-GC OR GP-GC	(a) BITUMINOUS (b) PORTLAND CEMENT	PI NOT TO EXCEED 10 PI NOT TO EXCEED 30		WELL-GRADED MATL ONLY MATL SHOULD CONTAIN AT LEAST 45% BY WT OF MATL PASSING NO. 4 SIEVE
		(c) LIME	PI NOT LESS THAN 12		
2 C	GM OR GC OR GM-GC	(a) BITUMINOUS	PI NOT TO EXCEED 10	NOT TO EXCEED 30% BY WT	WELL-GRADED MATL ONLY
		(b) PORTLAND CEMENT	PI NOT TO EXCEED NO. IND. BY EQ $20 + \frac{50 - \text{FINES CONT.}}{4}$		MATL SHOULD CONTAIN AT LEAST 45% BY WT OF MATL PASSING NO. 4 SIEVE
		(c) LIME	PI NOT LESS THAN 12		
3	CH OR CL OR MH OR ML OR OH OR OL OR ML-CL	(a) PORTLAND CEMENT	LIQUID LIMIT LESS THAN 40 AND PI LESS THAN 20		ORGANIC AND STRONGLY ACID SOILS FALLING WITHIN THIS AREA ARE NOT SUSCEPTIBLE OF STABILIZATION BY ORDINARY MEANS
		(b) LIME			

NOTE: (A) Soil classification corresponds to MIL-STD-619B. Restriction on Liquid Limit, Plastic Limit, and Plasticity Index is in accordance with Method 103 in MIL-STD-621A.

FIGURE 2. GRADATION TRIANGLE FOR AID IN SELECTING A COMMERCIAL STABILIZING AGENT.

[after U. S. Air Force (4)]

Oglesby and Hewes (5) have presented a method of determining stabilizer types which was modified after the original work of the Division of Physical Research, Bureau of Public Roads (Figure 3). This method utilizes the plasticity index (P.I.) and percent passing the No. 200 sieve together with the American Association of State Highway Officials (AASHO) Soil Classification System for the purpose of stabilizer selection.

3. Criteria for Lime Stabilization

Experience has shown that lime will react with all medium, moderately fine, and fine grained soils to decrease plasticity, increase workability, reduce swell, and increase strength (6). Generally speaking, those soils classified by AASHO as A-4, A-5, A-6, A-7 and some of the A-2-7 and A-2-6 soils are most readily susceptible to stabilization with lime. Soils classified according to the Unified System as CH, CL, MH, ML, SC, SM, GC, GM, SW-SC, SP-SC, SM-SC, GW-GC, GP-GC and GM-GC should be considered as potentially capable of being stabilized with lime. Conversion from these classifications to other soil classifications and strength indicators can be accomplished by the use of Figure 4 (7).

Robnett and Thompson (6), based on experience gained with Illinois soils, have indicated that lime may be an effective stabilizer with clay contents ($<2\mu$) as low as 7 percent, and furthermore soils with a P.I. as low as 8 can be satisfactorily stabilized with lime (8). Air Force criteria presented in Figure 2 indicate that the P.I. should be greater than 12, while representatives of the National Lime Association (NLA) (9) indicate that a P.I. greater than 10 would be a reasonable criteria to utilize. Presumably, these experiences reflect the fact that lower plasticity soils have insufficient reactive components to produce worthwhile benefits.

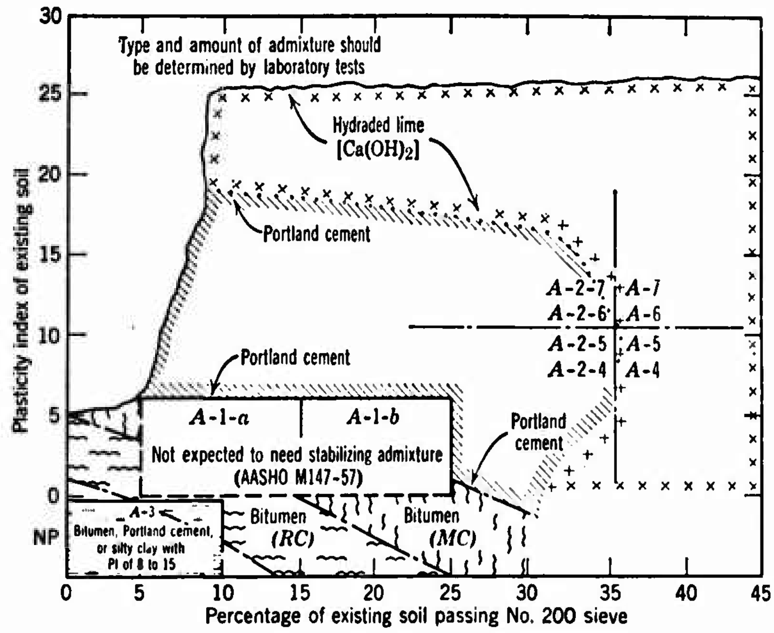
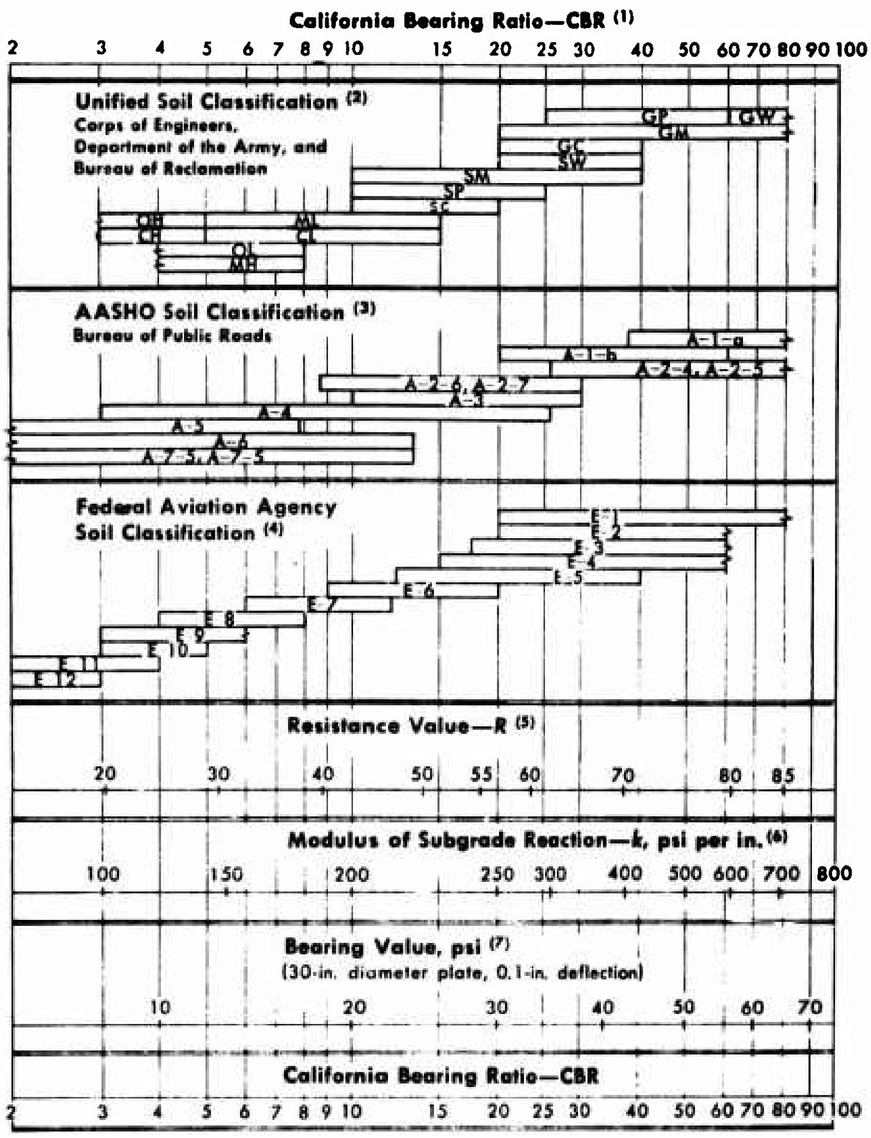


FIGURE 3. Suggested stabilizing admixtures suitable for use with soils, as indicated by plasticity index and amount passing No. 200 sieve. (Source: Div. of Physical Research, Bureau of Public Roads, slightly modified).

[after Oglesby & Hewes (5)]



(1) For the basic idea, see O. J. Porter, "Foundations for Flexible Pavements," Highway Research Board *Proceedings of the Twenty-second Annual Meeting*, 1942, Vol. 22, pages 100-136.

(2) "Characteristics of Soil Groups Pertaining to Roads and Airfields," Appendix B, *The Unified Soil Classification System*, U.S. Army Corps of Engineers, Technical Memorandum 3-357, 1953.

(3) "Classification of Highway Subgrade Materials," Highway Research Board *Proceedings of the Twenty-fifth Annual Meeting*, 1945, Vol. 25, pages 376-392.

(4) *Airport Paving*, U.S. Department of Commerce, Federal Aviation Agency, May 1948, pages 11-16. Estimated using values given in FAA *Design Manual for Airport Pavements*.

(5) F. N. Hveem, "A New Approach for Pavement Design," *Engineering News-Record*, Vol. 141, No. 2, July 8, 1948, pages 134-139. *R* is factor used in California Stabilometer Method of Design.

(6) See T. A. Middlebrooks and G. E. Bertram, "Soil Tests for Design of Runway Pavements," Highway Research Board *Proceedings of the Twenty second Annual Meeting*, 1942, Vol. 22, page 152. *k* is factor used in Westergaard's analysis for design of concrete pavement.

FIGURE 4. Approximate interrelationships of soil classifications and bearing values.

[after Portland Cement Association (7)]

4. Criteria for Cement Stabilization

The Portland Cement Association (PCA) (10, 11) indicates that all types of soils can be stabilized with cement*. However, well-graded granular materials that possess a floating aggregate matrix (an aggregate system with the voids in the + No. 200 material overfilled with fines) have given the best results. Suggested gradings to meet this floating aggregate matrix concept should fall within the band specified in Table 3 (12).

Limits on the plasticity index have been established by the Air Force as shown in Figure 2 and summarized in Table 4 for different types of soils. As noted, the P.I. should be less than 30 for the sandy and gravelly materials while the P.I. should be less than 20 for the fine grained soils. This limitation is necessary to insure proper mixing of the stabilizer. A minimum of 45 percent by weight passing the No. 4 sieve has been indicated as an additional requirement for coarse granular materials.

Information developed by the Bureau of Public Roads (Figure 3) (5) indicates that cement should be used as a stabilizer for materials with less than 35 percent passing the No. 200 sieve and with a P.I. less than 20. Thus this system implies that AASHO classified A-2 and A-3 soils can be best stabilized by cement while A-4, A-5, A-6 and A-7 soils can be best stabilized by lime.

5. Criteria for Bituminous Stabilization

The majority of bituminous soil stabilization has been performed with asphalt cement, cutback asphalt and asphalt emulsion. Current design and construction trends, particularly in the state highway departments, have

*Cement will be used herein to imply portland cement.

TABLE 3

GRADING LIMITS FOR CEMENT STABILIZATION

OF WELL GRADED GRANULAR MATERIALS

Sieve Size	Limits
Passing No. 4	≥ 55 percent
Passing No. 10	≥ 35 percent
Passing No. 10, retained No. 200	≥ 25 percent

[after Portland Cement Association (12)]

TABLE 4

ATTERBERG LIMIT REQUIREMENTS FOR CEMENT STABILIZED SOILS

Soil Classification (Unified Soil Classification System)	Atterberg Limit Requirement
SP-SM, SW-SM, SW-SC, SP-SC GW-GM, GP-GM, GW-GC GP-GC	P.I. < 30
SM, SC, SM-SC GM, GC, GM-GC	$P.I. \leq 20 + \frac{(50 - \text{fines content})}{4}$
CH, CL MH, ML OH, OL ML-CL	L.L. < 40 P.I. < 20

[after U. S. Air Force (4)]

indicated that stabilization of base courses with asphalt cements is by far the most popular form of bituminous stabilization (13). In general, those materials which are most effectively stabilized with asphalt cement have lower percentages of fines than those materials which have been stabilized with cutback asphalt and emulsion.

Some of the earliest criteria for bituminous stabilization were developed by the Highway Research Board Committee on Soil-Bituminous Roads. These criteria were revised and published by Winterkorn (14) and appear in Table 5. The American Road Builders Association (15) made similar recommendations and these are shown in Table 6.

The Asphalt Institute (16) grading and plasticity requirements for bituminous base course specifications require:

a. less than 25 percent passing the No. 200 sieve

b. sand equivalent not less than 25

c. plasticity index less than 6

Herrin has presented (17) and revised (18) a table (Table 7) recommending suitable soils for stabilization by bituminous materials. Contained in this table are recommendations on the suitability of various soils with certain percentages of minus No. 200 material, and certain liquid limit and plasticity index ranges.

Certain limits have been developed by the Asphalt Institute's Pacific Coast Division, Chevron Asphalt Company and Douglas Oil Company for emulsion treated materials. The requirements recommended by the Asphalt Institute (19) (Table 8) suggest that the percent of minus No. 200 material should be in a range of 3-15 percent, the plasticity index should be less than 6, and the product of the plasticity index and the percent passing the No. 200 sieve should not exceed 60. The Chevron Asphalt Company (20) has presented

TABLE 5

TYPES OF SOIL BITUMEN AND CHARACTERISTICS OF SOILS

EMPIRICALLY FOUND SUITABLE FOR THEIR MANUFACTURE

Sieve Analysis	Soil Bitumen, † %	Sand Bitumen, %	Waterproofed Granular Stabilization, %		
Passing:			A	B	C
1 1/2-in.	...	...	100		
1-in.	‡	...	80-100	100	
3/4-in.	...	...	65-85	80-100	100
No. 4	>50	100	40-65	50-75	80-100
No. 10	...	...	25-50	40-60	60-80
No. 40	35-100	...	15-30	20-35	30-50
No. 100	...	...	10-20	13-23	20-35
No. 200	10-50	<12; <25 § ||	8-12	10-16	13-30
Characteristics of Fraction Passing No. 40 Sieve					
Liquid limit	<40	...	...	...	...
Plasticity index	<18	...	<10; <15	<10; <15	<10; <15 ¶
Field moisture equiv.	...	<20 §	...	...	...
Linear shrinkage	...	<5 §	...	...	...

† Proper or general.

‡ Maximum size not larger than 1/3 of layer thickness; if compacted in several layers, not larger than thickness of one layer.

§ Lower values for wide and higher values for narrow gradation band of sand. If more than 12% passes, restrictions are placed as indicated on field moisture equivalent and linear shrinkage.

|| A certain percentage of -200 or filler material is indirectly required to pass supplementary stability test.

¶ Values between 10 and 15 permitted in certain cases.

[after Winterkorn (14)]

TABLE 6

GRADING AND PLASTICITY REQUIREMENTS

FOR SOIL-BITUMEN MIXTURES

Sieve Size	Percent Passing
No. 40	50 - 100
No. 200	0 - 35
Atterberg Limits	**Maximum Value**
Liquid limit	30
Plasticity index	10

[after American Road Builders Association (15)]

TABLE 7

ENGINEERING PROPERTIES OF MATERIALS

SUITABLE FOR BITUMINOUS STABILIZATION

% Passing Sieve	Sand-Bitumen	Soil-Bitumen	Sand-Gravel-Bitumen
1-1/2"			100
1"	100		
3/4"			60-100
No. 4	50-100	50-100	35-100
10	40-100		
40		35-100	13-50
100			8-35
200	5-12	good - 3-20 fair - 0-3 and 20-30 poor - > 30	0-12
Liquid Limit		good - < 20 fair - 20-30 poor - 30-40 unusable - > 40	
Plasticity Index	< 10	good - 5 fair - 5-9 poor - 9-15 unusable - > 12-15	<10

Includes slight modifications later made by Herrin.

[after Herrin (17)]

TABLE 8

GRADING, PLASTICITY AND ABRASION REQUIREMENTS FOR

SOILS SUITABLE FOR EMULSIFIED ASPHALT TREATED BASE COURSE

Sieve Size	Percent Passing by Weight		
	2 inch maximum	1-1/2 inch maximum	3/4 inch maximum
2-1/2 inch	100		
2 inch	90-100	100	
1-1/2 inch		90-100	
1 inch			100
3/4 inch	50-80	50-80	80-100
No. 4	25-50	25-50	25-50
No. 200	3-15	3-15	3-15

Other Requirements

a. Plasticity Index 6 maximum
b. Resistance Value 75 minimum
c. Loss in Los Angeles Abrasion Machine 50 percent maximum
d. Product of Plasticity Index and the percent passing the No. 200 sieve shall not exceed 60.

[after The Asphalt Institute, Pacific Division (19)]

criteria (Table 9) which indicate that the California sand equivalent test should be used as a measure of the plasticity requirements for the soil and should have a minimum value of 30. Up to 25 percent passing the No. 200 sieve is allowed for the material identified as silty sand.

Dunning and Turner (21) of the Douglas Oil Company have presented guidelines for emulsion stabilization as shown in Table 10.

Materials Research and Development, Inc. of Oakland, California, has recently published a guide for asphalt stabilization for the U. S. Navy (22) in which criteria recommended by the Asphalt Institute and Chevron Asphalt Company have been utilized. This guide recommends that the maximum amount passing the No. 200 sieve should be less than 25 percent, the plasticity index less than 6, sand equivalent more than 30, and the product of the plasticity index and the percent passing the No. 200 sieve less than 72 in all cases. These criteria apply when both cutback asphalt and emulsified asphalt are used as soil stabilizers. The grading requirements (Table 11) for sands and semi-processed materials are identical to those recommended in Table 9 by Chevron Asphalt Company.

Grading requirements for materials to be stabilized with asphalt cement in a central plant have not been adequately defined. In general, those materials that are specified as suitable for asphalt concrete surface courses are more than adequate for base courses. Most asphalt treated base course specifications, however, will allow a larger maximum size of aggregate and the grading band is not as restrictive. A recent review of state highway specifications gives detailed information on these grading bands (13). For example, Texas (23) and California (24) have grading specifications as shown in Table 12. In addition, Texas specifies a maximum liquid limit of 35 and a maximum plasticity index of 6. The majority of the state highway depart-

TABLE 9

TYPICAL AGGREGATES SUITABLE FOR TREATMENT WITH BITUMULS EMULSIFIED ASPHALTS

Category	ASTM Test Method	Processed[1] Dense Graded Aggregates	SANDS			Semi-Processed Crusher, Pit or Bank Run Aggregates
			Poorly Graded	Well Graded	Silty Sands	
Gradation: 1½" % Passing		100				100
1"		90-100				80-100
¾"		65-90				—
½"		—	100	100	100	—
# 4		30-60	75-100	75-100	75-100	25-85
16	C-136	15-30	—	35-75	—	—
50		7-25	—	15-30	—	—
100		5-18	—	—	15-65	—
200		4-12	0-12	5-12	12-25	3-15
Sand Equivalent, %	D-2419	30 Min.	30 Min.	30 Min.	30 Min.	30 Min.
Plasticity Index	D-424	—	NP	NP	—	—
Untreated Resistance R Value	*	78 Min.	60 Min.	60 Min.	60 Min.	60 Min.
Loss in Los Angeles Rattler (after 500 revolutions)	C-131	50 Max.	—	—	—	60 Max.

[1]Must have at least 25% Crush Count
*See AASHO T-174, T-175, and T-176

[after Chevron Asphalt Co. (20)]

TABLE 10

GUIDELINES FOR EMULSIFIED ASPHALT STABILIZATION

Test	Requirements		
	Good	Fair	Poor
% passing No. 200 sieve	3 - 20	0 - 3, 20 - 30	>30
Sand Equivalent	>25	15 - 25	<15
Plasticity Index	< 5	5 - 7	> 7

[after Dunning and Turner (21)]

TABLE 11

GRADING REQUIREMENTS FOR SANDY AND SEMI-PROCESSED MATERIALS

Sieve Size	Percent passing sieve for soils that are:			
	Poorly-graded sands	Well-graded sands	Silty sands	Semi-processed*
1 1/2"	--	--	--	100
1"	--	--	--	80 - 100
3/4"	--	--	--	--
1/2"	100	100	100	--
#4	75 - 100	75 - 100	75 - 100	25 - 85
#16	--	35 - 75	--	--
#50	--	15 - 30	--	--
#100	--	--	15 - 65	--
#200	0 - 25	5 - 12	12 - 25	3 - 15

*Semi-processed crusher, pit, or bank-run aggregates.

[after U. S. Navy (22)]

TABLE 12

TYPICAL ASPHALT CEMENT TREATED BASE COURSE REQUIREMENT

Sieve Size	Percent Passing by Weight	
	California	Texas
1 3/4 inch		97-100
1 1/4 inch	100	
1 inch	95-100	
3/4 inch	80-95	
3/8 inch	50-65	
No. 4	35-50	
No. 10		30-55
No. 30	12-25	
No. 200	2-7	

[after references 23 and 24]

ments recommended 12 percent or less passing the No. 200 sieve.

Air Force recommendations for gradings of materials suitable for asphalt cement treated base course are shown in Table 13 (25). Although gradations 6, 7, 8 and 9 are specifically recommended, it is believed that all gradations are practical, provided they are economically feasible.

Materials that are suitable for bituminous treatment include AASHO classified A-1-a, A-1-b, A-2-4, A-2-6, A-3, A-4 and low plasticity A-6 soils (26), and soils classified by the Unified Classification System as SW, SP, SW-SM, SP-SM, SW-SC, SP-SC, SM, SC, SM-SC, GW, GP, GW-GM, GP-GM, GW-GC, GP-GC, GM, GC and GM-GC provided certain plasticity and grading requirements are met.

If the plasticity index or the percent passing the No. 200 sieve exceeds the values cited above, then experience shows that the intimate mixing of the bitumen and soil necessary for satisfactory stabilization is nearly impossible.

6. Criteria for Combination Stabilization

Combination stabilization is herein defined specifically as lime-cement or lime-bituminous combinations. The purpose of using combination stabilizers is to reduce plasticity and increase workability with lime so that the soil may be effectively stabilized with the secondary stabilizer.

Robnett and Thompson (26) have reviewed the literature and have suggested that soils which may be treated by these combination stabilizers are AASHO classified A-6 and A-7 soils and certain A-4 and A-5 soils (6)

The advantages of using lime in certain bituminous stabilization construction operations have been alluded to in references 27, 28 and 29. Most importantly, the addition of lime may prevent the stripping of asphalts from certain aggregates and thus make the mix more nearly waterproof.

TABLE 13

AGGREGATE GRADATION SPECIFICATION LIMITS FOR BITUMINOUS PAVEMENTS

Percentage by Weight (Passing)

Surface Course

Sieve Designation (Square Openings)	1-1/2-in. Maximum: Gradation 1 a	b	c	1-in. Maximum: Gradation 2 a	b	c	3/4-in. Maximum: Gradation 3 a	b	c	1/2-in. Maximum: Gradation 4 a	b	c	3/8-in. Maximum: Gradation 5 a	b	c
1-1/2-in.	100	100	100	---	---	---									
1-in.	79-95	83-96	86-98	100	100	100	---	---	---						
3/4-in.	---	---	---	80-95	84-96	90-98	100	100	100	---	---	---			
1/2-in.	61-75	66-79	71-84	68-86	74-89	79-93	80-95	84-96	87-98	100	100	100	---	---	---
3/8-in.	---	---	---	---	---	---	---	---	---	79-94	81-95	86-96	100	100	100
No. 4	42-54	48-60	54-66	45-60	52-68	60-75	55-70	61-74	67-80	59-73	64-80	72-85	75-95	78-95	80-95
No. 10	31-43	37-49	43-55	32-47	39-54	47-62	40-54	46-60	54-66	43-57	50-64	57-70	56-76	60-80	62-84
No. 40	16-25	20-29	25-34	16-26	21-32	26-37	22-31	26-35	31-40	23-33	27-37	31-42	26-44	29-47	32-50
No. 80	10-17	12-19	15-22	10-18	13-21	15-24	12-20	15-23	19-26	13-20	16-23	19-26	14-28	16-30	18-32
No. 200*	3-6	3.5-6.5	4-7	3-7	3.5-7.5	4-8	3-7	3.5-7.5	4-8	4-8	4-8	4-8	5-9	6-10	7-11

Binder Course

Sieve Designation (Square Openings)	1-1/2-in. Maximum: Gradation 6 a	b	c	1-in. Maximum: Gradation 7 a	b	c	3/4-in. Maximum: Gradation 8 a	b	c	1/2-in. Maximum: Gradation 9 a	b	c
1-1/2-in.	100	100	100	---	---	---						
1-in.	73-95	75-95	79-95	100	100	100	---	---	---			
3/4-in.	---	---	---	72-95	75-95	81-96	100	100	100	---	---	---
1/2-in.	55-73	59-77	62-80	61-82	65-85	69-89	70-95	74-95	77-95	100	100	100
3/8-in.	---	---	---	---	---	---	60-80	64-84	68-88	71-95	75-95	78-95
No. 4	35-51	39-55	42-58	38-54	43-59	48-66	42-60	47-65	52-70	50-71	54-75	59-80
No. 10	23-38	27-42	31-46	25-41	29-45	34-50	28-46	33-51	36-54	32-53	36-57	41-62
No. 40	11-21	13-23	15-25	12-23	14-25	17-28	14-26	16-28	18-30	16-29	18-31	21-34
No. 80	6-14	7-15	8-16	7-16	8-17	10-18	8-18	9-19	10-20	10-20	11-21	12-22
No. 200*	3-7	3-7	3-7	3-7	3-7	3-7	3-7	3-7	3-7	4-9	4-9	4-9

All High-pressure Tire and Tar-rubber Surface Courses

Sieve Designation (Square Openings)	1-in. Maximum: Gradation 10 a	b	c	3/4-in. Maximum: Gradation 11 a	b	c
1-in.	100	---	---	---	---	---
3/4-in.	84-97	---	---	100	---	---
1/2-in.	74-88	---	---	82-96	---	---
3/8-in.	68-82	---	---	75-90	---	---
No. 4	54-67	---	---	60-73	---	---
No. 10	38-51	---	---	43-57	---	---
No. 20	26-39	---	---	29-43	---	---
No. 40	17-30	---	---	19-33	---	---
No. 80	9-19	---	---	10-20	---	---
No. 200*	3-6	---	---	3-6	---	---

[after U. S. Army (25)]

7. Summary of Criteria for Selecting Stabilizing Agents

Criteria have been presented which represent wide ranges of opinion as to the types of soils that can be stabilized by certain stabilizers. Most published information gives reference to soils classified either by the AASHO or Unified Soil Classification Systems; however, the authors feel that a more appropriate separation of soils for stabilization can be made utilizing Atterberg limits and gradation. It should be remembered that both Atterberg limits and gradation are relatively easy to determine in the laboratory and both are necessary inputs for the AASHO and Unified Soil Classification Systems.

Criteria selected for utilization in this index system are based on the recommendations cited previously and by personal conversation with representatives of the University of Washington, Washington State University, University of Idaho, University of California, Oregon Highway Department, United States Forest Service, Chevron Asphalt Company, Asphalt Institute, Portland Cement Association, National Lime Association and private consultants. It should be recognized that unaminous agreement was not possible on the selection of these criteria. The criteria selected are as follows:

I. Expedient construction

   A. Subgrade

      1. Lime stabilization

         Minimum plasticity index of 10

      2. Cement stabilization

         Maximum plasticity index of 30

      3. Bituminous stabilization

         a. Maximum plasticity index of 10

b. Maximum of 25 percent passing No. 200 sieve

4. Lime-Cement stabilization

   a. Minimum soil plasticity index of 10
   b. Minimum of 25 percent passing No. 200 sieve
   c. Reduce plasticity index of soil to less than 30 with lime prior to the addition of cement

5. Lime-Bituminous stabilization

   a. Minimum soil plasticity index of 10
   b. Minimum of 25 percent passing No. 200 sieve
   c. Reduce plasticity index of soil to less than 10 with lime prior to the addition of the bitumen

B. Base course

1. Lime stabilization

   Minimum plasticity index of 10

2. Cement stabilization

   Maximum plasticity index of 30

3. Bituminous stabilization

   a. Maximum plasticity index of 6
   b. Maximum of 25 percent passing No. 200 sieve
   c. Product of plasticity index and percent passing No. 200 sieve less than or equal to 72

4. Lime-Cement stabilization

   a. Minimum soil plasticity index of 10
   b. Minimum of 25 percent passing No. 200 sieve
   c. Reduce plasticity index of soil to less than 30 with lime prior to the addition of cement

5. Lime-Bituminous stabilization

   a. Minimum soil plasticity index of 10
   b. Minimum of 25 percent passing No. 200 sieve
   c. Reduce plasticity index of soil to less than 6 with lime prior to the addition of bitumen

II. Nonexpedient construction

A. Subgrade

1. Lime stabilization

Minimum plasticity of index of 10

2. Cement stabilization

Maximum plasticity index of 30

3. Bituminous stabilization

a. Maximum plasticity index of 10
b. Maximum of 25 percent passing No. 200 sieve

4. Lime-Cement stabilization

a. Minimum soil plasticity index of 10
b. Minimum of 25 percent passing No. 200 sieve
c. Reduce plasticity index of soil to less than 30 with lime prior to the addition of cement

5. Lime-Bituminous stabilization

a. Minimum soil plasticity index of 10
b. Minimum of 25 percent passing No. 200 sieve
c. Reduce plasticity index of soil to less than 10 with lime prior to the addition of the bitumen

B. Base course

1. Lime stabilization

Minimum plasticity index of 10

2. Cement stabilization

Maximum plasticity index of 30

3. Bituminous stabilization

a. Maximum plasticity index of 6
b. Maximum of 25 percent passing No. 200 sieve
c. Product of plasticity index and percent passing No. 200 sieve less than or equal to 60

4. Lime-Cement stabilization

a. Minimum soil plasticity index of 10
b. Minimum of 25 percent passing No. 200 sieve
c. Reduce plasticity index of soil to less than 30 with lime prior to the addition of cement

5. Lime-Bituminous stabilization

a. Minimum soil plasticity index of 10

b. Minimum of 25 percent passing No. 200 sieve
c. Reduce plasticity index of soil to less than 6 with lime prior to the addition of bitumen

Adoption of the above criteria allows the development of Figures 5, 6, 7 and 8 which serve as the intitial breakdown of the soils into groups with which soil stabilizers can be associated. Because of the relative simplicity of the tests involved, the system can be used with minor alterations for both expedient and nonexpedient construction operations. As noted on Figures 5 and 6, slightly different criteria are used for base and subgrade stabilization for the reasons cited previously.

The engineer should be aware of certain environmental conditions and construction limitations that restrict the use of the stabilizers. Listings of these conditions in the form of precautions for lime, cement and bituminous stabilization are given in Tables 14, 15 and 16, respectively.

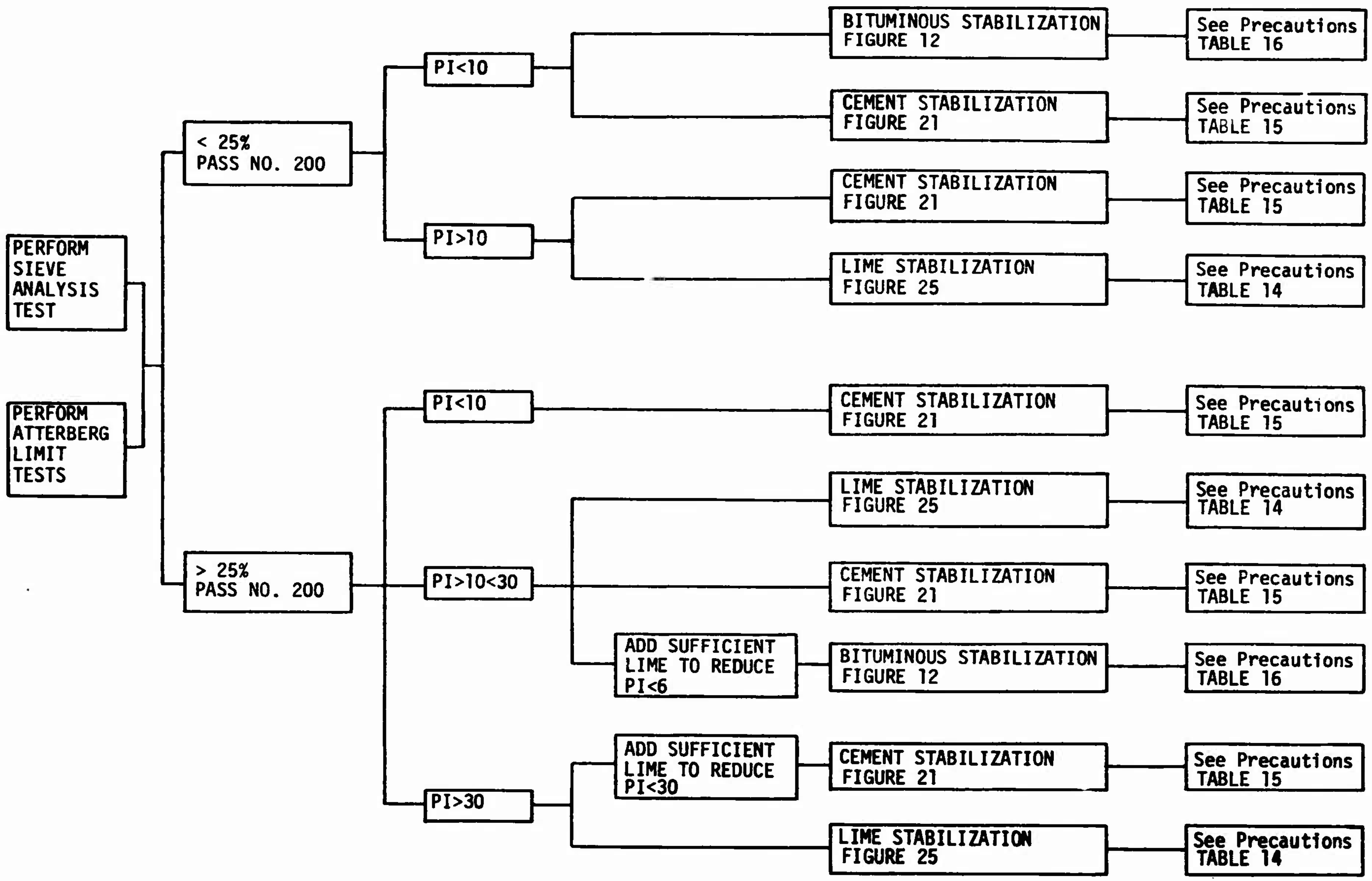


FIGURE 5. SELECTION OF STABILIZER FOR EXPEDIENT SUBGRADE CONSTRUCTION

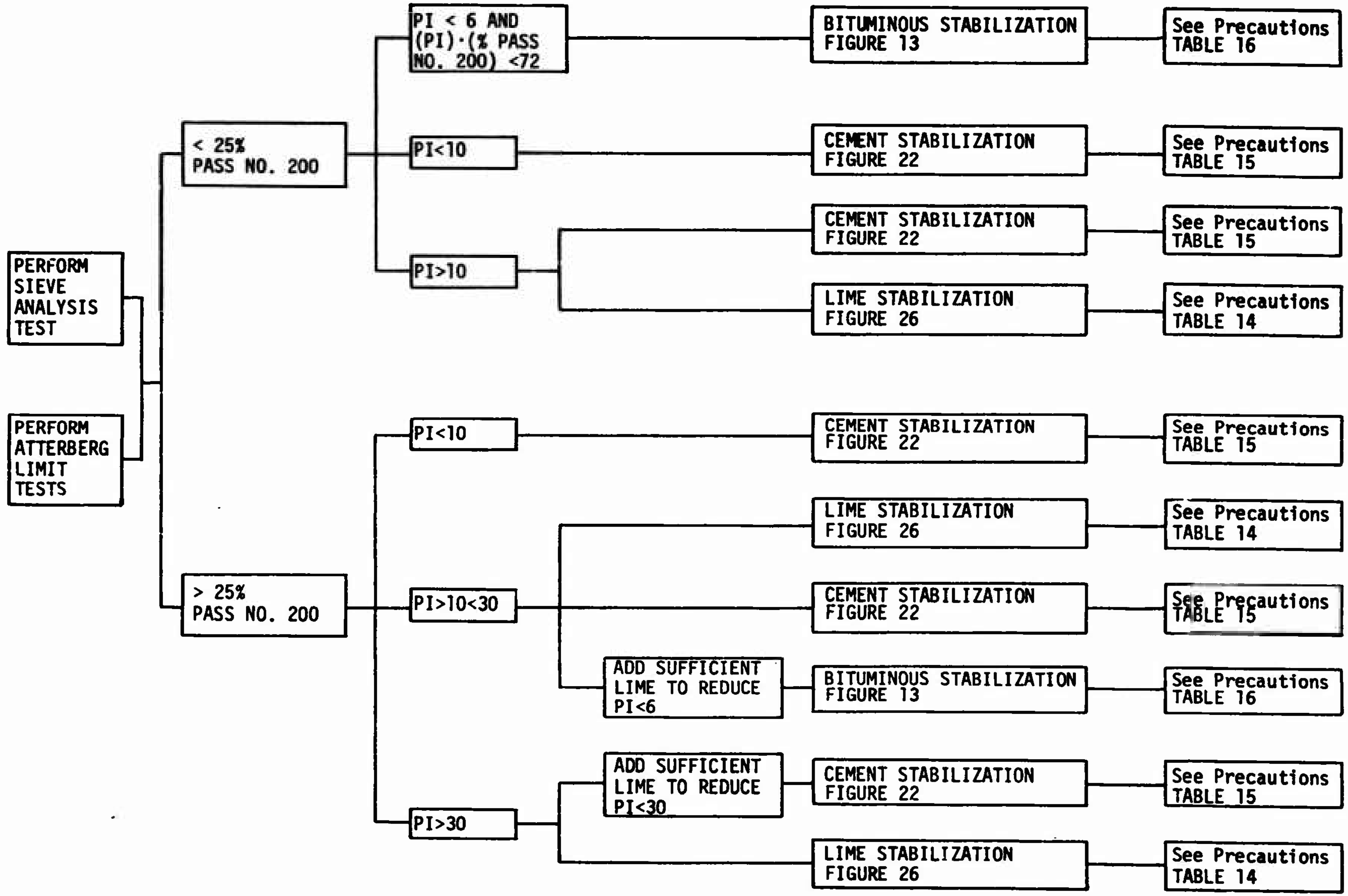


FIGURE 6. SELECTION OF STABILIZER FOR EXPEDIENT BASE CONSTRUCTION

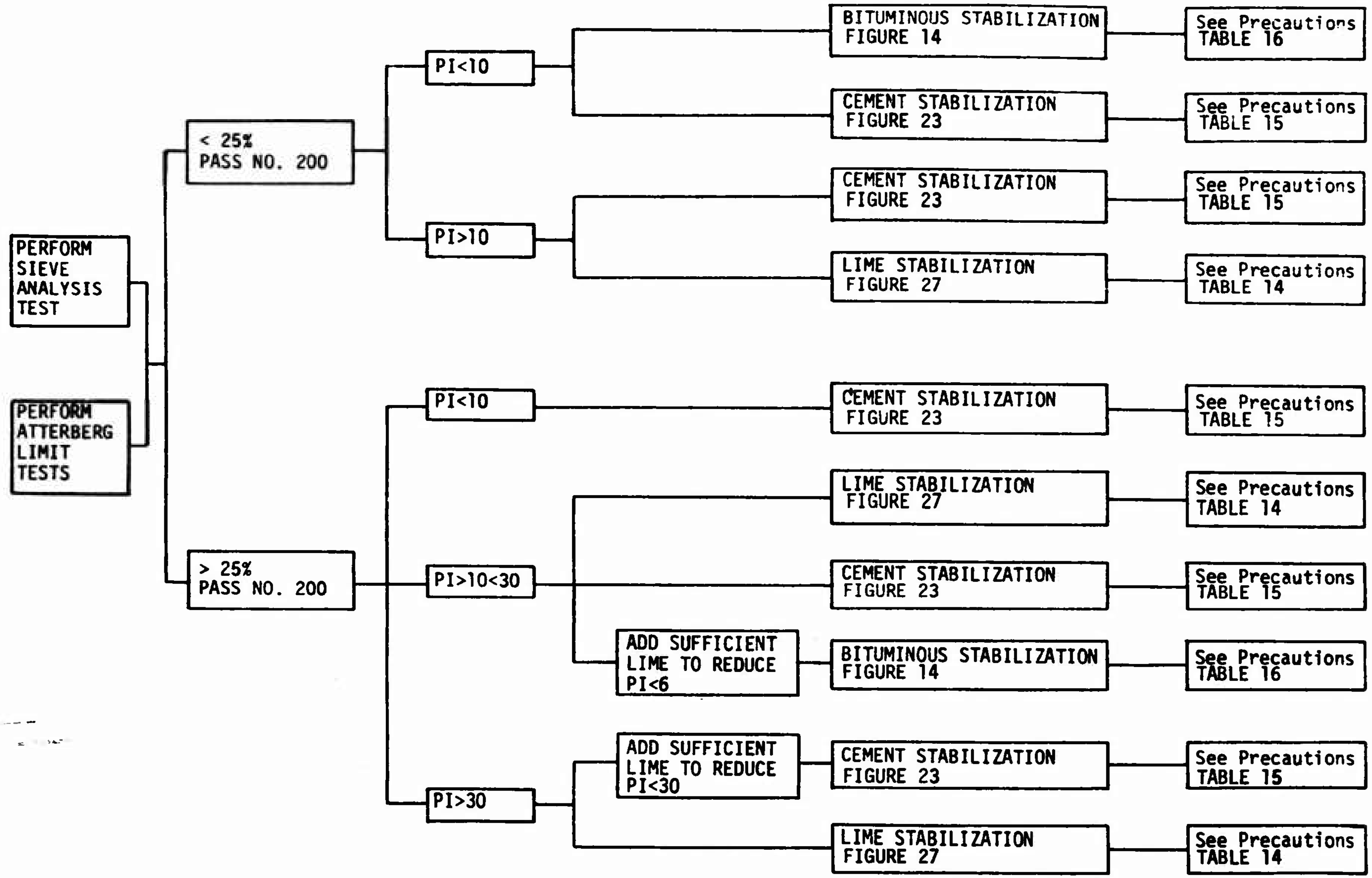


FIGURE 7. SELECTION OF STABILIZER FOR NONEXPEDIENT SUBGRADE CONSTRUCTION

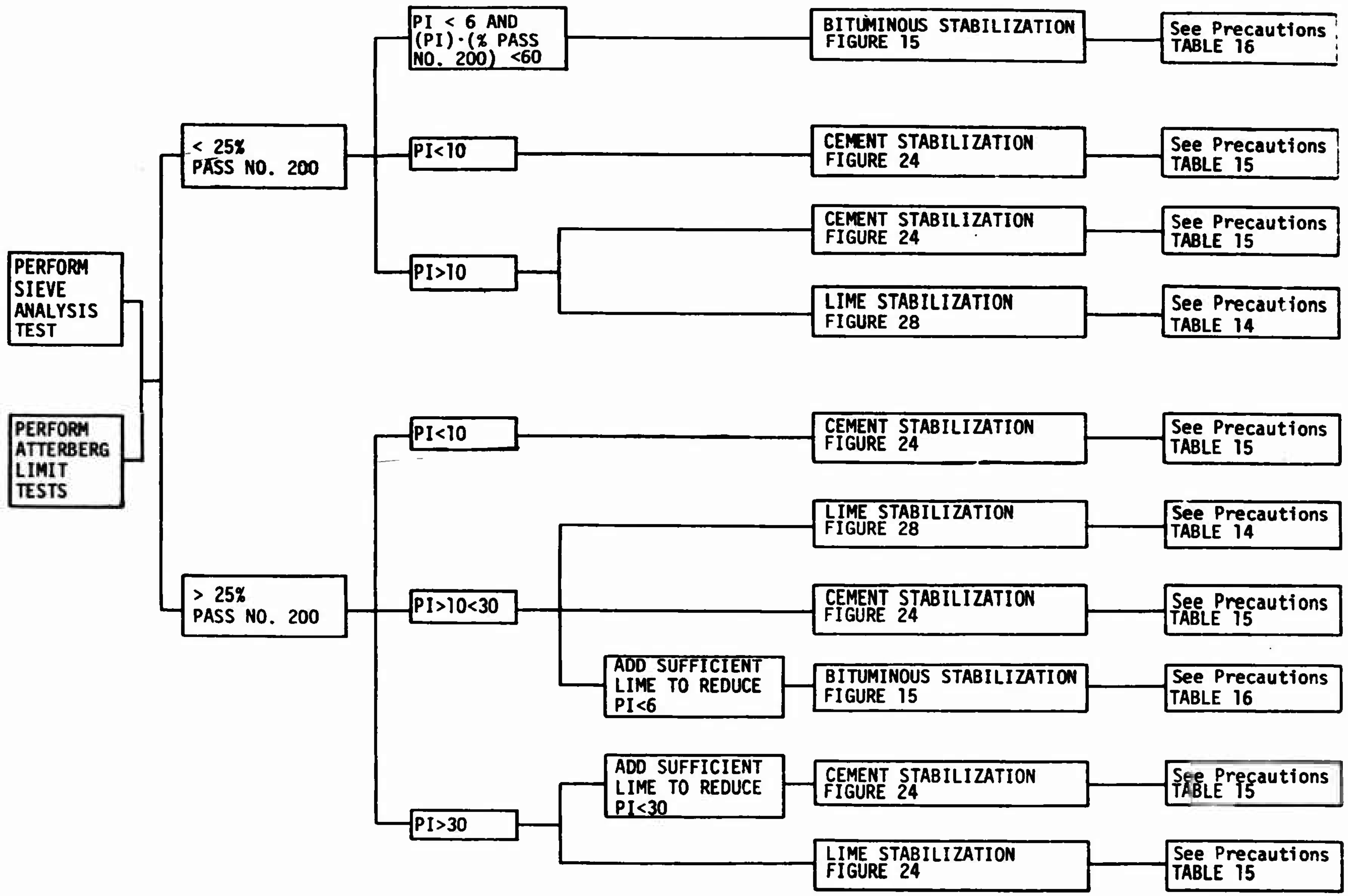


FIGURE 8. SELECTION OF STABILIZER FOR NONEXPEDIENT BASE CONSTRUCTION

TABLE 14

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR LIME STABILIZATION

Item	Location of Stabilized Layer
I	**Expedient Subgrades** A. Environmental - If the soil temperature is less than 40°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and the strength gain of the lime-soil mixture will be minimal. If these environmental conditions are expected the lime may act as a soil modifier. B. No construction precautions necessary.
II	**Expedient Base Courses** A. Environmental - If the soil temperature is less than 60 to 70°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and the strength gain of the lime-soil mixture will be minimal. If these environmental conditions are expected an alternative stabilizer should be investigated for possible use. B. Construction - If heavy vehicles are allowed on the lime stabilized soils prior to a 10 to 14 day curing period, certain pavement damage can be expected.
III	**Nonexpedient Subgrades** A. Environmental - If the soil temperature is less than 60 to 70°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and the strength gain of the lime-soil mixture will be minimal. If these environmental conditions are expected the lime may act as a soil modifier. Lime-soil mixtures should be scheduled for construction such that sufficient durability will be gained to resist any freeze-thaw cycles expected. B. Construction - If heavy vehicles are allowed on the lime stabilized soils prior to a 10 to 14 day curing period, certain pavement damage can be expected.
IV	**Nonexpedient Base Courses** A. Environmental - If the soil temperature is less than 60 to 70°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and the strength gain of the lime-soil mixture will be minimal. If these environmental conditions are expected the lime may be expected to act as a soil modifier. Lime-soil mixtures should be scheduled for construction such that sufficient durability will be gained to resist any freeze-thaw cycles expected. B. Construction - If heavy vehicles are allowed on the lime stabilized soils prior to a 10 to 14 day curing period, certain pavement damage can be expected.

TABLE 15

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR CEMENT STABILIZATION

Item	Location of Stabilized Layer
I	**Expedient Subgrades** A. Environmental - If the soil temperature is less than 40°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and strength gain of the cement-soil mixture will be minimal. If these environmental conditions are expected the cement may act as a soil modifier. B. Construction - If heavy vehicles are allowed on the cement stabilized soils prior to a 10 to 14 day curing period, certain pavement damage can be expected. Construction during periods of heavy rainfall should be avoided. Compaction of cement stabilized soil should be completed within 5 to 6 hours after spreading and mixing.
II	**Expedient Base Courses** A. Environmental - If the soil temperature is less than 60 to 70°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and strength gain of the cement-soil mixture will be minimal. If these environmental conditions are expected, an alternative stabilizer should be investigated for possible use. B. Construction - If heavy vehicles are allowed on the cement stabilized soils prior to a 10 to 14 day curing period, certain pavement damage can be expected.
III	**Nonexpedient Subgrades** A. Environmental - If the soil temperature is less than 60 to 70°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and strength gain of the cement-soil mixture will be minimal. If these environmental conditions are expected the cement may act as a soil modifier. Cement-soil mixtures should be scheduled for construction such that sufficient durability will be gained to resist any freeze-thaw cycles expected. B. Construction - If heavy vehicles are allowed on the cement stabilized soils prior to a 10 to 14 day curing period, certain pavement damage can be expected.
IV	**Nonexpedient Base Courses** A. Environmental - If the soil temperature is less than 60 to 70°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and strength gain of the cement-soil mixture will be minimal. If these environmental conditions are expected the cement may be expected to act as a soil modifier. Cement-soil mixtures should be scheduled for construction such that sufficient durability will be gained to resist any freeze-thaw cycles expected. B. Construction - If heavy vehicles are allowed on the cement stabilized soils prior to a 10 to 14 day curing period, certain pavement damage can be expected.

TABLE 16

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR BITUMINOUS STABILIZATION

Condition	Precautions
Environmental	When asphalt cements are used for bituminous stabilization, proper compaction must be obtained. If thin lifts of asphalt concrete are being placed, the air temperature should be 40°F and rising, and compaction equipment should be used immediately after lay down operation. Adequate compaction can be obtained at freezing temperatures if thick lifts are utilized. When cutbacks and emulsions are utilized, the air temperature and soil temperature should be above freezing. Bituminous materials should completely coat the soil particles before rainfall stops construction.
Construction	Central batch plants, together with other specialized equipment, are necessary for bituminous stabilization with asphalt cements. Hot dry weather is preferred for all types of bituminous stabilization.

(Note: These requirements are applicable to base courses and subgrades for both expedient and nonexpedient operations.)

SECTION IV

DESIGN SUBSYSTEM FOR BITUMINOUS STABILIZATION

1. Introduction

The majority of bituminous stabilization construction is performed with asphalt cements, cutback asphalts, and emulsified asphalts. Road tars have been used, but it is felt that sufficient quantities have not been utilized to warrant their inclusion in this index system. Soils which lend themselves to stabilization with the above mentioned bituminous materials have been defined in Section III of this report. In order to complete a design subsystem for bituminous stabilization, criteria must be included to allow for the following:

a. selection of the type of bitumen

b. selection of the quantity of bitumen

c. method of evaluating the bitumen-soil mixture

This section of the report will summarize criteria recommended by various agencies and will select what is believed to be the best criteria for use in the bituminous stabilization subsystem.

2. Selection of the Type of Bitumen

An indication of the type of bitumen to use for certain types of soils has been suggested by the Asphalt Institute (16), Herrin (17), the Navy (22), the Air Force (30) and Chevron Asphalt Company (20). The Asphalt Institute (16) suggestions are shown in Table 17 while the recommendations of Herrin (17),

TABLE 17

SUITABLE TYPES OF BITUMEN FOR STABILIZATION

Type of Soils	Cutback Asphalts	Emulsions
Open-graded aggregate	RC-250, RC-800	MS-2
Well-graded aggregate with little or no fine aggregate and material passing the No. 200 sieve	RC-250, RC-800 MC-250, MC-800 SC-250, SC-800	MS-2 SM-K SS-1, SS-K
Aggregate containing a considerable percentage of fine aggregate and material passing the No. 200 sieve	MC-250, MC-800 SC-250, SC-800	SS-1, SS-1h SS-K, SS-Kh MS-2 CM-K

[after the Asphalt Institute (16)]

which are similar, are shown in Table 18.

The Navy's (22) method to select emulsions and cutback asphalts is shown in Table 19 and Figure 9, respectively. The selection of the particular type of emulsion is based on the percent of the soil passing the No. 200 sieve and the relative water content of the soil, while the selection of the particular type of cutback asphalt is based on the percent passing the No. 200 sieve and the ambient temperature of the soil. The basis of selection between these two general kinds of asphalt depends on which kind is more readily available for a particular job. Air Force (30) recommendations are very general in nature and indicate the MC-70, MC-250, MC-800, RC-70, RC-250, RC-800 cutbacks and SS-1 emulsions are normally used. Soils which possess some fines or natural binders and are well graded can be stabilized with medium curing cutbacks; however, the rapid curing cutbacks are preferred.

Chevron Asphalt Company (20) recommends emulsions that conform to the specifications shown in Table 20. The selection of either a cationic or anionic emulsion should be based on the type of aggregate that is used. Mertens and Wright (31) have developed a method by which an aggregate can be classified (Figure 10) to indicate its probable surface charge and to determine the type of emulsion (anionic or cationic) that is more suitable for the particular type of aggregate (Figure 11). In general, Chevron recommends SS and CM type emulsions with damp or wet aggregate mixes.

The use of asphalt cement stabilization is widespread in the highway departments in the United States. Seventy-one percent of all bituminous bound base courses placed by the state highway agencies in 1968 were made with asphalt cement and mixed in a hot plant (13). In addition, several cities and counties are using this type of stabilization. It is therefore important that its advantages be fully explored by the Air Force.

TABLE 18

SUITABLE TYPES OF BITUMINOUS MATERIALS

Sand-Bitumen	Soil-Bitumen	Crushed Stones and Sand-Gravel-Bitumen
Hot Mix: (a) AC- 85-100 120-150 (b) 85-100 100-120 120-150	Cold Mix: RC-70,250,800 (a) (b) MC-70,250,800 SC-70,250,800	Hot Mix: (a) AC- 85-100 120-150 (b) 85-100 100-120 120-150
Cold Mix: (a) (b) RC-70,250,800 MC-250,800		Cold Mix: (a) (b) RC-70,250,800 MC-250,800
Emulsions (a) (b) SS-1 (a) SS-1h SS-K SS-Kh SM-K	Emulsions (a) (b) SS-1 (a) SS-1h SS-K SS-Kh SM-K	Emulsions (a) (b) SS-1 MS-2 (a) CM-K

(a) Refers to Asphalt Institute Nomenclature.

(b) Refers to Illinois Division of Highways Nomenclature.

[after Herrin (17)]

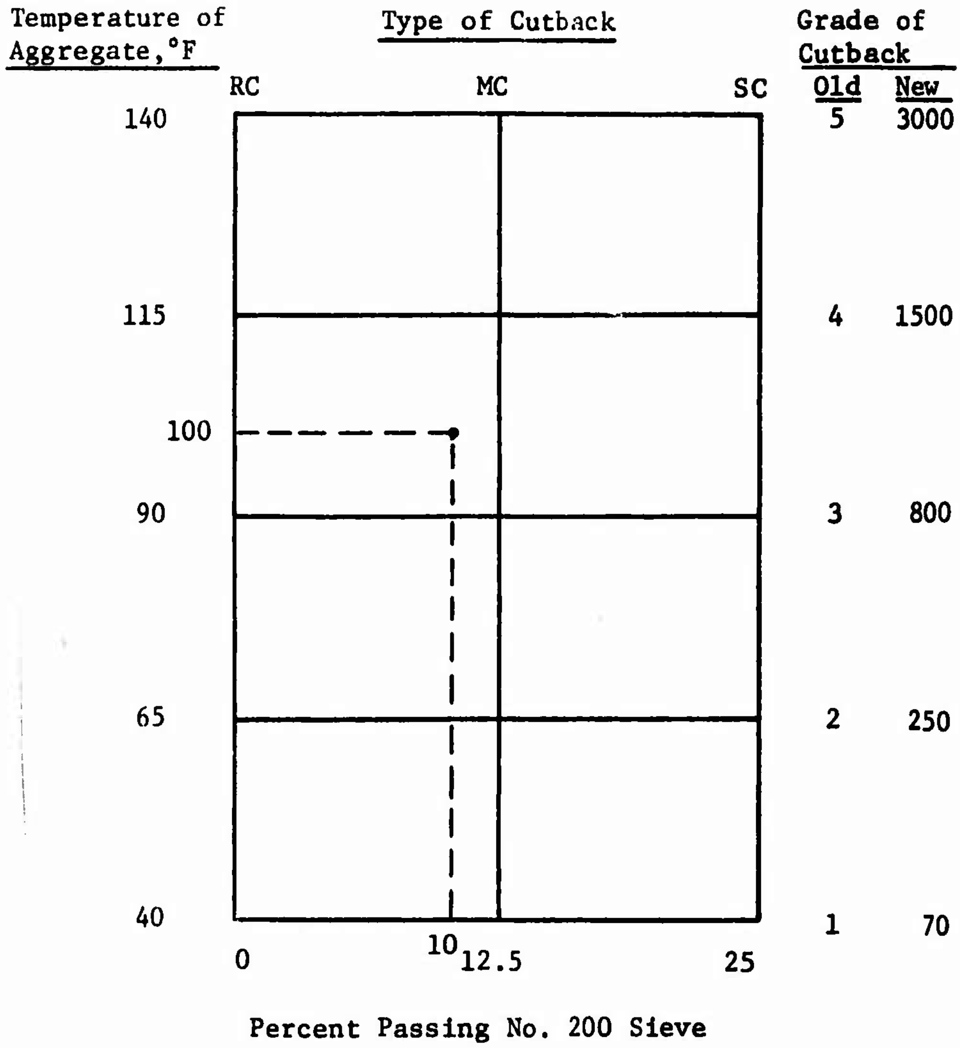
TABLE 19

SELECTION OF TYPE OF EMULSIFIED ASPHALT FOR STABILIZATION

Percent Passing # 200 Sieve	Relative Water Content of Soil	
	Wet (5%+)	Dry (0-5%)
0-5	SS-1h (or SS-Kh)	SM-K (or SS-1h*)
5-15	SS-1, SS-1h (or SS-K, SS-Kh)	SM-K (or SS-1h*, SS-1*)
15-25	SS-1 (or SS-K)	SM-K

*Soil should be pre-wetted with water before using these types of emulsified asphalts.

[after U. S. Navy (22)]



Example: For aggregate temperature of 100°F and 10% passing #200 sieve, use MC 800 cutback.

FIGURE 9. Selection of type of cutback for stabilization [after U. S. Navy (22)]

TABLE 20

CHEVRON ASPHALT COMPANY PRODUCT SPECIFICATIONS FOR BITUMULS EMULSIFIED ASPHALT MIXING GRADES

ASTM Method	Test Designation	ANIONIC CM-3 Min.-Max.	ANIONIC DM-1 Min.-Max.	ANIONIC DM-1h Min.-Max.	ANIONIC DM-2 Min.-Max.	CATIONIC CM-K Min.-Max.	CATIONIC SM-K Min.-Max.	CATIONIC SS-K Min.-Max.	CATIONIC SS-Kh Min.-Max.
D-244	Viscosity, Saybolt-Furol @ 77°F — Sec.	—	20-100	20-100	50-400	—	—	20-100	20-100
D-244	Viscosity, Saybolt-Furol @ 122°F — Sec.	50-500	—	—	—	50-500	50-500	—	—
D-244	Storage Stability	— 1.0	— 1.0	— 1.0	— 1.0	— 1.0	— 1.0	— 1.0	— 1.0
D-244	Settlement 7 Days, per cent	— 5.0	— 5.0	— 5.0	— 5.0	— 5.0	— 5.0	— 5.0	— 5.0
D-244	Sieve Test, per cent	— 0.10	— 0.10	— 0.10	— 0.10	— 0.10	— 0.10	— 0.10	— 0.10
D-244	Cement Mixing, per cent	—	— 2.0	— 2.0	— 2.0	—	—	— 2.0	— 2.0
*D-244	Coating Ability and Water Resistance, per cent	80 Dry Ag. 60 Wet Ag.	— —	— —	— —	80 Dry Ag. 60 Wet Ag.	— —	— —	— —
**	Dehydration Ratio (100°F) (96 hrs.)	—	—	—	—	—		0.70 —	0.70 —
D-244	Particle Charge	—	—	—	—	Positive	Positive	—	—
E-70	pH	—	—	—	—	—	—	— 6.5	— 6.5
D-244	Residue by Distillation, %	63 —	55 —	55 —	60 —	65 —	60 —	58 —	58 —
	Oil Distillate, % by Volume	5-11	—	—	—	— 12	— 15	—	—

Tests on Residue from Distillation

ASTM Method	Test Designation	CM-3	DM-1	DM-1h	DM-2	CM-K	SM-K	SS-K	SS-Kh
D-5	Penetration, 77° F, 100g. 5 sec.	100-200	100-200	40-90	100-200	100-250	100-250	100-200	40-90
D-2042	Solubility in trichlorethylene	97 —	97 —	97 —	97 —	97 —	97 —	97 —	97 —
D-113	Ductility @ 77° F, Cm.	40 —	40 —	40 —	40 —	40 —	40 —	40 —	40 —

*With following modifications: 1. Made on Unwashed Air-dried Job Aggregate. 2. Use "2 minutes" Mixing instead of "5 minutes" in Sec. 51.4. 3. Replace "Immediately" with "After 30 minutes" in Sec. 51.6.

**Method described in ASTM Bulletin 101.

[after Chevron Asphalt Company (20)]

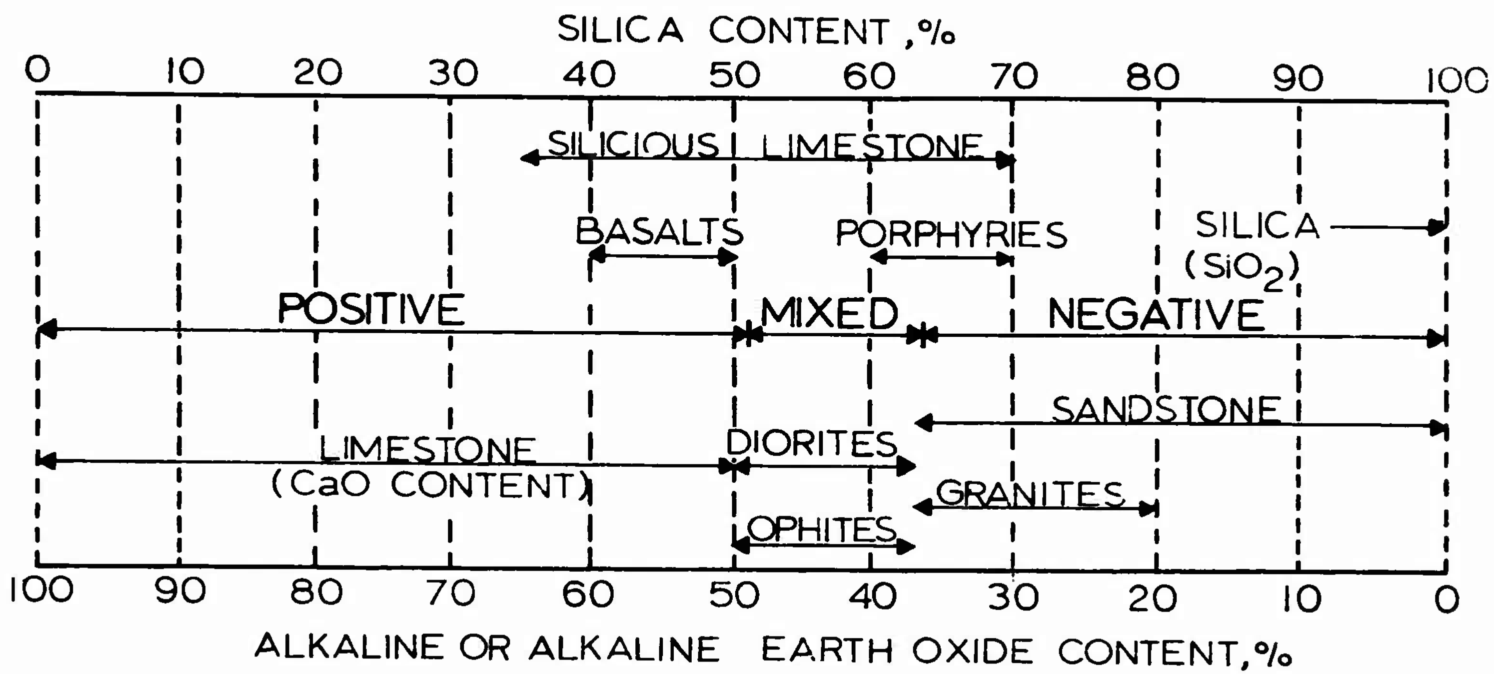


FIGURE 10. Classification of aggregates

[after Mertens and Wright (31)]

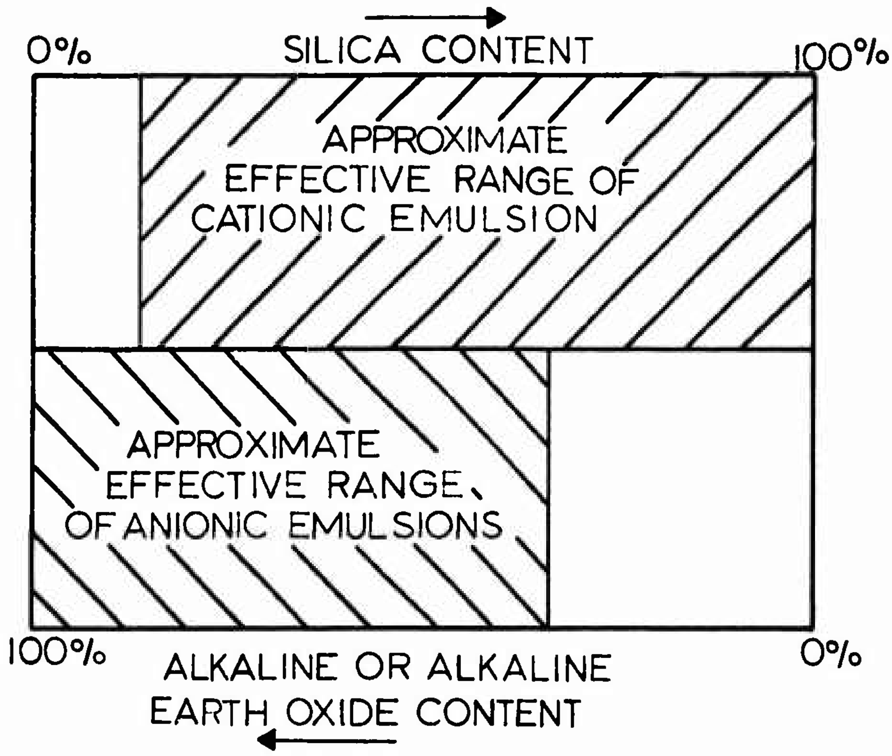


FIGURE 11. Approximate effective range of cationic and anionic emulsions on various types of aggregates

[after Mertens and Wright (31)]

Federal specifications for asphalt cements, cutback asphalts and emulsified asphalts are given in Tables 21, 22 and 23 respectively. These specifications closely parallel those recommended by the Asphalt Institute (16).

3. Selection of the Quantity of Bitumen

Methods which have been used for the determination of asphalt content for stabilized materials can be conveniently separated into methods based on laboratory tests performed on the soil, methods based on laboratory tests performed on the soil-asphalt mixture and those based on a combination of these two. A discussion of these methods follows.

a. Methods based on laboratory tests performed on the soil

These approaches are based on the quantity of asphalt necessary to coat the surface of the soil particles. A general equation for computing the quantity of asphalt is:

$$A = SA \times t \times \gamma_a$$

where:

A = percent asphalt

t = asphalt film thickness

SA = surface area of soil or aggregate

γ_a = unit weight of asphalt

This equation has been quantified empirically by the Asphalt Institute (16), Oklahoma Department of Highways (32), McKesson (33) and Bird (34).

The Oklahoma Equation (32) developed for cutback asphalts has the following form:

$$p = k + 0.005 (a) + 0.01 (b) + 0.06 (c)$$

TABLE 21

SPECIFICATIONS FOR ASPHALT CEMENT

Penetration Grade, Designation	Penetration 50-60 AP-6	60-70 AP-5	70-85 AP-4	85-100 AP-3	100-200 AP-2	120-150 AP-1
Water*	The material shall be free from water					
Specific gravity, 77°/77°F**	------	------	------	------	------	------
Flash point (Cleveland Open Cup) °F	347+	347+	347+	347+	347+	347+
Softening point, °F**	104-140	104-140	104-140	104-140	95-131	95-131
Penetration 77°F, 100 gm., 5 sec.	50-60	60-70	70-85	85-100	100-120	120-150
Ductility, 77°F, cm.	40+	40+	40+	-------	-------	-------
Loss on heating, 325°F, 5 hr., Percent	1-	1-	1-	1-	1-	1-
Penetration of residue, 77°F, 100 gm., 5 sec., % of original	60+	60+	60+	60+	60+	60+
Solubility in carbon disulfide, Percent	99.5+	99.5+	99.5+	99.5+	99.5+	99.5+
Insoluble organic matter, Percent	0.2-	0.2-	0.2-	0.2-	0.2-	0.2-
Spot test, standard naptha solvent†	Negative for all grades of petroleum asphalt					
Application Temperature, °F	250-325	250-325	250-325	250-325	250-325	250-325

* General requirement. The material shall be homogeneous, free from water, and shall not foam when heated to 346°F.

** Uniformity. The material furnished under Fed. Spec. SS-A-706b for a given contract, type, and grade shall be uniform in character, and samples from deliveries shall not vary more than + 41°F in softening point, within the limits specified above, nor more than ± 0.010 in specific gravity, from the results of tests on a representative sample furnished by the contractor prior to delivery.

† Not a part of specification SS-A-706b.

[taken from Federal Specification SS-A-706b.]

TABLE 22

SPECIFICATIONS FOR CUTBACK ASPHALTS

Grades	Rapid Curing						Medium Curing					
	RC-0	RC-1	RC-2	RC-3	RC-4	RC-5	MC-0	MC-1	MC-2	MC-3	MC-4	MC-5
Water	The material shall be free from water						The material shall be free from water					
Flash point (Tag. open cup), °F	------	------	80+	80+	80+	80+	100+	100+	150+	150+	150+	150+
Furol viscosity at:												
77°F	75-150	------	------	------	------	------	75-100	------	------	------	------	------
122°F	------	75-150	------	------	------	------	------	75-100	------	------	------	------
140°F	------	------	100-200	250-500	------	------	------	------	100-120	250-500	------	------
180°F	------	------	------	------	125-250	300-600	------	------	------	------	125-250	300-600
Distillation:												
Distillate (% total distillate to 680°F)												
To 374°F	15+	10+	------	------	------	------	------	------	------	------	------	------
To 437°F	55+	50+	40+	25+	8+	------	25-	20-	10-	5-	0	0
To 500°F	75+	70+	65+	55+	40+	25+	40-70	25-65	15-55	5-40	30-	20-
To 600°F	90+	88+	87+	83+	80+	70+	75-93	70-90	60-87	55-85	40-80	20-75
Residue from distillation to 680°F, volume, % of sample, by difference	50+	60+	67+	73+	78+	82+	50+	60+	67+	73+	78+	82+
Tests on residue from distillation:												
Penetration 77°F, 100 gm., 5 sec.	80-120	80-120	80-120	80-120	80-120	80-120	120-300	120-300	120-300	120-300	120-300	120-300
Ductility 77°F, 5 cm. per sec., cm.*	100+	100+	100+	100+	100+	100+	100+	100+	100+	100+	100+	100+
Percent soluble in carbon tetrachloride	99.5+	99.5+	99.5+	99.5+	99.5+	99.5+	99.5+	99.5+	99.5+	99.5+	99.5+	99.5+
Spot test, standard naptha solvent**	Negative for all grades						Negative for all grades					

Grades	Slow Curing					
	SC-0	SC-1	SC-2	SC-3	SC-4	SC-5
Water, %	0.5-	0.5-	0	0	0	0
Flash point (Cleveland open cup), °F	150+	150+	175+	200+	225+	250+
Furol viscosity at:						
77°F	75-150	------	------	------	------	------
122°F	------	75-150	------	------	------	------
140°F	------	------	100-200	250-500	------	------
180°F	------	------	------	------	125-250	300-600
Asphalt residue of 100 penetration, percent	40+	50+	60+	70+	75+	80+
Distillation:						
Total distillate to 680°F, percent by volume	15-40	10-30	5-25	2-15	10	5-
Tests on residue from distillation:						
Float test at 122°F, sec.	15-100	20-100	25-100	50-125	60-150	75-200
Ductility at 77°F, cm.	100+	100+	100+	100+	100+	100+
Percent soluble in carbon tetrachloride***	99.5+	99.5+	99.5+	99.5+	99.5+	99.5+
Application temperatures, °F	50-120	80-125	150-200	175-250	175-250	200-275

* For medium curing cutbacks, if penetration of residue is more than 200 and its ductility at 77°F is less than 100, the material will be acceptable if its ductility at 60°F is 100+.

** Not part of specification

*** If the material fails to meet the requirement for solubility, it will be acceptable if its solubility in CS_2 is 99%+ and the proportion of bitumen soluble in CCl_4 is 99.65%+.

[taken from Federal Specifications SS-A-671a]

TABLE 23

SPECIFICATIONS FOR EMULSIONS

Tests	ANIONIC Rapid Setting RS-1	RS-2	Medium Setting MS-1	MS-2	Slow Setting SS-1	SS-1h
TESTS ON EMULSION						
Viscosity, Furol, 60 ml., 77°F, sec.	20-100	--	--	100-700	20-100	20-100
Viscosity, Furol, 60 ml., 122°F., sec.	--	75-400	50-500	--	--	--
Residue by distillation, percent	57-62	62-69	60-67	62-69	57-62	57-62
Settlement, 7 day, maximum, difference	3	3	3	3	3	3
Demulsibility:						
50 ml. 0.10 N $CaCl_2$, percent	--	--	--	0-30	--	--
35 ml. 0.02 N $CaCl_2$, percent	60+	60+	--	--	--	--
Sieve test, maximum, percent	0.10	0.10	0.10	0.10	0.10	0.10
Miscibility with water, hours	--	--	--	2	--	--
Aggregate Coating-Water Resistance test	--	--	Pass	--	--	--
Cement mixing test, maximum percent	--	--	--	--	2.0	2.0
Oil Distillate, percent by volume, max.	--	--	12	--	--	--
TESTS ON RESIDUE FROM DISTILLATION TEST						
Penetration, 77°F., 100 gm., 5 sec.	100-200	100-200	100-200	100-200	100-200	40-90
Soluble in CCl_4, minimum percent	97	97	97	97	97	97
Ash, maximum, percent	2	2	2	2	2	2
Ductility at 77°F, minimum, cm.	40	40	40	40	40	40

Tests	CATIONIC Rapid Setting RS-2K	RS-3K	Medium Setting SM-K	CM-K	Slow Setting SS-K	SS-Kh
TESTS ON EMULSION						
Viscosity, Furol, 60 ml., 77°F, sec.	--	--	--	--	20-100	20-100
Viscosity, Furol, 60 ml., 122°F, sec.	20-100	100-400	50-500	50-500	--	--
Residue by distillation, percent	60-65	65-72	60-65	65-72	57-62	57-62
Settlement, 7 day, max., difference	3	3	3	3	3	3
Sieve test, maximum, percent	0.10	0.10	0.10	0.10	0.10	0.10
Aggregate Coating-Water Resistance test						
Dry Aggregate (Job), min. pct. coated	--	--	80	80	--	--
Wet Aggregate (Job), min. pct. coated	--	--	60	60	--	--
Cement mixing test, maximum percent	--	--	--	--	2	2
Particle Charge test	Positive	Positive	Positive	Positive	--	--
pH, maximum	--	--	--	--	6.5	6.5
Oil Distillate, percent by volume, max.	5	5	20	12	--	--
TESTS ON RESIDUE FROM DISTILLATION TEST						
Penetration, 77°F., 100 gm., 5 sec.	100-250	100-250	100-250	100-250	100-200	40-90
Soluble in CCl_4, minimum, percent	98	98	98	98	97	97
Ductility at 77°F., minimum, cm.	40	40	40	40	40	40

[taken from Federal Specification SS-A-00674C]

where:

p = percent of residual asphalt by weight of dry aggregate

a = percent mineral aggregate passing the No. 10 sieve

b = percent mineral aggregate passing the No. 40 sieve

c = percent mineral aggregate passing the No. 200 sieve

k = 1.5 if plasticity index ≤ 8 and 2.0 if plasticity index > 8

The Asphalt Institute (16) adopted a method for use with cutbacks and emulsions as follows:

1. Cutbacks

$$p = 0.02\ (a) + 0.07\ (b) + 0.15\ (c) + 0.20\ (d)$$

where:

p = percent of residual asphalt by weight of dry aggregate

a = percent of mineral aggregate retained on No. 50 sieve

b = percent of mineral aggregate passing No. 50 sieve and retained on No. 100 sieve

c = percent of mineral aggregate passing No. 100 sieve and retained on No. 200 sieve

d = percent of mineral aggregate passing No. 200 sieve

2. Emulsions

$$p = 0.05\ (a) + 0.1\ (b) + 0.5\ (c)$$

where:

p = percent by weight of asphalt emulsion, based on dry weight of mineral aggregate

a = percent of mineral aggregate retained on No. 8 sieve

b = percent of mineral aggregate passing No. 8 sieve and retained on the No. 200 sieve

c = percent of mineral aggregate passing the No. 200 sieve

This equation has also been utilized by the Navy (22) for cutback stabilization.

McKesson's (35) formula, given below, is similar in form to the Asphalt Institute's formula:

$$P = 0.75\ (0.05A + 0.010B + 0.50C)$$

where:

P = percent of asphalt emulsion by weight of dry sand

A = sand retained on the No. 10 sieve in percent

B = sand passing the No. 10 sieve and retained on the No. 200 sieve in percent

C = sand passing the No. 200 sieve in percent

Bird (34) has presented two formulas to use depending on the percent passing the No. 200 sieve.

Formula (1) $T = 0.02F + 0.1C + 4$

(for use with sands having a minimum of 50 percent passing the No. 10 sieve and 5 to 12 percent passing the No. 200 sieve)

Formula (2) $T = 0.2F + 0.1D + 4$

(for use with sands having a minimum of 50 percent passing the No. 10 sieve and more than 12 percent passing the No. 200 sieve)

where:

T = pounds of emulsified asphalt per cubic foot of loose, dry aggregate

F = percent aggregate passing the No. 10 sieve

C = percent aggregate passing the No. 200 sieve

D = difference, plus or minus, between 24 and C above

The California Centrifuge Kerosene Equivalent (CKE) Method is based on surface area as well as particle surface characteristics. The com-

plete California CKE Method can be found in California Test Method 303 (35); however, a revised method has been suggested for use by the Navy (22). The CKE method is suitable for asphalt cement, cutback, and emulsified asphalt stabilized materials.

The Navy (22) has also suggested emulsion quantities to be used for certain soils based on the percent passing the No. 10 sieve and percent passing the No. 200 sieve (Table 24). The development of the table was based on surface area and void content theory.

b. Methods based on laboratory tests performed on the soil-asphalt mixture

Several laboratory test methods have been used to assist the engineer in determining the asphalt content of stabilized mixtures. For convenience these can be separated into:

1. Methods for use with hot-mix asphalt cement stabilized materials
2. Methods for use with liquid asphalts (cutbacks and emulsions).

A recent Highway Research Board Committee Report (13) has summarized design methods and criteria used for coarse aggregate type hot plant mixed bases. As shown on Table 25 the Hveem and Marshall methods of design are in popular use, but the criteria vary from state to state. Several states indicated the use of Marshall stability and unconfined compressive strength; however, they did not indicate criteria. Three states (Oregon, Washington and Wyoming) indicated the use of modified immersion-compression tests.

Marshall method criteria utilized by the Air Force (2) are shown in Table 26. The criteria listed for asphaltic concrete binder course are suitable for use with coarse graded aggregate hot-mix base courses while the criteria for sand-asphalt should be used for these particular types of asphalt cement treated materials. The Air Force has indicated that the

TABLE 24

EMULSIFIED ASPHALT REQUIREMENT

Percent passing No. 200	Lbs. of emulsified asphalt per 100 lbs. of dry aggregate when percent passing No. 10 sieve is:					
	50*	60	70	80	90	100
0	6.0	6.3	6.5	6.7	7.0	7.2
2	6.3	6.5	6.7	7.0	7.2	7.5
4	6.5	6.7	7.0	7.2	7.5	7.7
6	6.7	7.0	7.2	7.5	7.7	7.9
8	7.0	7.2	7.5	7.7	7.9	8.2
10	7.2	7.5	7.7	7.9	8.2	8.4
12	7.5	7.7	7.9	8.2	8.4	8.6
14	7.2	7.5	7.7	7.9	8.2	8.4
16	7.0	7.2	7.5	7.7	7.9	8.2
18	6.7	7.0	7.2	7.5	7.7	7.9
20	6.5	6.7	7.0	7.2	7.5	7.7
22	6.3	6.5	6.7	7.0	7.2	7.5
24	6.0	6.3	6.5	6.7	7.0	7.2
25	6.2	6.4	6.6	6.9	7.1	7.3

*50 or less.

[after U. S. Navy (22)]

TABLE 25

DESIGN METHODS AND CRITERIA FOR COARSE AGGREGATE HOT MIX BASE COURSES

A. Hveem Method

State	Stability	Percent Air Voids	Percent Voids Filled With Asphalt	Cohesiometer
California	35 minimum	4-6		
Colorado	30-45	3-5	80-85	
Hawaii	35 minimum	5-10	75	300 minimum
Nevada	30-37 min.	3-5		
Oklahoma	35 minimum	8 maximum		
Oregon	30 minimum	10 maximum		150 minimum
Texas	30 minimum			
Washington	20 minimum			50 minimum

B. Marshall Method

State	Stability lbs.	Flow Value 0.001 in.	Percent Air Voids	Percent Voids Filled With Asphalt
District of Columbia	750 minimum	8-16	3-8	65-75
Georgia	1800 minimum	8-16	3-6	65-75
Kansas	800-3000	5-15	1-5	70-85
Kentucky	1100-1500	12-15	4-6	
Mississippi	1600	16 maximum	5-7	50-70
New Jersey	1100-1500	6-18	3-7	
N. Carolina	800	7-14	3-8	
N. Dakota	400 minimum	8-18	3-5	
Pennsylvania	700 minimum	6-16		60-85
Rhode Island	750 minimum		3-8	
S. Carolina	1200-3000	6-12		
S. Dakota		8-18	3-5	
Wyoming	100 minimum			

C. Unconfined Compressive Strength

State	Load, psi	Percent Air Voids	Percent Voids Filled With Asphalt
Colorado	200-400	3-5	80-85
Oregon	150 minimum		

[after Highway Research Board (13)]

TABLE 26

CRITERIA FOR DETERMINATION OF OPTIMUM BITUMEN CONTENT
(Marshall Method)

Test Property	Type of Mix	Point on Curve: For 100 psi tires[1]	Point on Curve: For 200 psi tires[1]	Criteria: For 100 psi tires[1]	Criteria: For 200 psi tires[1]
Stability	Asphaltic-concrete surface course	Peak of curve	Peak of curve	500 lb or higher	1800 lb or higher
	Asphaltic-concrete binder course	Peak of curve[2]	Peak of curve[2]	500 lb or higher	1800 lb or higher
	Sand asphalt	Peak of curve		500 lb or higher	
Unit weight	Asphaltic-concrete surface course	Peak of curve	Peak of curve	Not used	Not used
	Asphaltic-concrete binder course	Not used	Not used	Not used	Not used
	Sand asphalt	Peak of curve		Not used	Not used
Flow	Asphaltic-concrete surface course	Not used	Not used	20 or less	16 or less
	Asphaltic-concrete binder course	Not used	Not used	20 or less	16 or less
	Sand asphalt	Not used	Not used	20 or less	16 or less
Percent voids total mix	Asphaltic-concrete surface course	4 (3)	4 (3)	3-5 (2-4)	3-5 (2-4)
	Asphaltic-concrete binder course	5 (4)	6 (5)	4-6 (3-5)	5-7 (4-6)
	Sand asphalt	6 (5)	-- (-)	5-7 (4-6)	--- (---)
Percent voids filled with bitumen	Asphaltic-concrete surface course	80 (85)	75 (80)	75-85 (80-90)	70-80 (75-85)
	Asphaltic-concrete binder course	70 (75)	60 (65)[2]	65-75 (70-80)	70-80 (55-75)
	Sand asphalt	70 (75)	-- (--)	65-75 (70-80)	-- (--)

[1] Figures in parentheses are for use with bulk impregnated specific gravity (water absorption greater than 2.5 percent).

[2] If the inclusion of asphalt contents of these points in the average causes the voids to fall outside the limits, then the optimum asphalt content should be adjusted so that the voids total mix are within the limits.

[after U. S. Air Force (2)]

asphalt content determined by the Marshall method should be altered depending upon the Pavement Temperature Index and the Traffic Area (Table 27). Howver, these criteria were developed for surface courses and do not appear to be warranted for base courses.

The Asphalt Institute (36) recommends three popular criteria for use in hot-mix base course design (Table 28). Specifically, the Asphalt Institute recommends the same criteria that are utilized for surface courses, but the test temperature is 100°F rather than 140°F. This recommendation applies to regions having climatic conditions similar to those prevailing throughout most of the United States and provided the base is 4 inches or more below the surface. Existing information suggests that most base courses at this depth do not reach a temperature in excess of 100°F, and, therefore, the 100°F testing temperature has been selected.

Zoepf (cited in reference 37) has also recommended Marshall criteria based on studies conducted in Germany (Table 29).

McDowell and Smith (38) have recently presented a design procedure based on unconfined compressive strength and air voids criteria for the selection of the asphalt content. This method includes the effect of the rate of loading on the properties of asphalt treated materials.

Recent attempts have been made to develop a more rational approach to pavement design. Among others, Monismith (39, 40) has indicated that "elastic" properties and fatigue properties of the asphalt treated base courses should be considered in pavement design. Testing methods have been developed to measure these properties (41, 42, 43, 44) and should be considered for possible utilization by the Air Force.

The above mentioned tests are generally considered as a measure of

TABLE 27

BITUMEN CONTENT AND PENETRATION GRADE OF ASPHALT FOR VARIOUS TEMPERATURE INDEX RANGES

		Bitumen Content by Traffic Areas								
		Type A Traffic Areas			Types B and C Traffic Areas			Type D Traffic Areas (2)		
Pavement Temp. Index	Asphalt Pen. Grade	Light Load Pavements	Intermediate Load Pavements (1)	Heavy Load Pavements	Light Load Pavements	Intermediate Load Pavements	Heavy Load Pavements	Light Load Pavements	Intermediate Load Pavements	Heavy Load Pavements
Negative	120-150	---	Optimum	(3)	Opt. +10%	Opt. +10%	Optimum	---	Opt. +10%	Opt. +10%
0-40	100-120	---	Optimum	(3)	Optimum	Optimum	Opt. -10%	---	Opt. +10%	Opt. +10%
40-100	85-100	---	Opt. -10%	(3)	Optimum	Optimum	Opt. -20%	---	Opt. +10%	Optimum
Above 100	60-70	---	Opt. -20%	(3)	Optimum	Opt. -10%	(3)	---	Optimum	Optimum

(1) Intermediate load pavements, for the purposes of this tabulation, include those for the twin bicycle, twin tricycle, and twin-tandem tricycle gear configurations for which design criteria are included in this manual.
(2) Blast zones within overrun areas are included with type D traffic areas.
(3) Design bitumen content to be furnished by OCE at time of airfield design.

PAVEMENT TEMPERATURE INDEX:

The sum, for a one-year period, of the increments above 75°F of monthly averages of the daily maximum temperatures. Average daily maximum temperatures for the period of record should be used where 10 or more years of record are available. For records of less than 10-year duration the record for the hottest year should be used. A negative index results when no monthly average exceeds 75°F. Negative indices are evaluated merely by subtracting the largest monthly average from 75°F.

[after U. S. Air Force (2)]

TABLE 28

MIXTURE DESIGN CRITERIA

A. Marshall Design Criteria

Traffic Category	Heavy		Medium		Light	
Test Property	Min.	Max.	Min.	Max.	Min.	Max.
No. of Compaction Blows Each End of Specimen	75		50		35	
Stability, all mixtures	750	---	500	---	500	---
Flow, all mixtures	8	16	8	18	8	20
Percent Air Voids						
Surfacing or Leveling	3	5	3	5	3	5
Base	3	8	3	8	3	8
Percent Voids in Mineral Aggregate						

B. Hveem Design Criteria

Traffic Category	Heavy		Medium		Light	
Test Property	Min.	Max.	Min.	Max.	Min.	Max.
Stabilometer Value	37	---	35	---	30	---
Cohesiometer Value	50	---	50	---	50	---
Swell	less than 0.030 inch					

C. Hubbard-Field Design Criteria

Traffic Category	Heavy		Medium and Light	
Test Property	Min.	Max.	Min.	Max.
Stability-Pounds	2,000	---	1,200	2,000
Percent Air Voids	2%	5%	2%	5%

Hot-mix asphalt bases, which do not meet the above criteria when tested at 140°F., should be satisfactory if they meet the criteria when tested at 100°F. and are placed 4 inches or more below the surface. This recommendation applies only to regions having climatic conditions similar to those prevailing throughout most of the United States. Guidelines for applying for the lower test temperature in regions having more extreme climatic conditions are being studied.

[after The Asphalt Institute (36)]

TABLE 29

MARSHALL MIX DESIGN CRITERIA

FOR ASPHALT CEMENT TREATED BASE COURSE

Marshall Requirement at 140°F	Traffic, Vehicles per day			
	Light (less than 3000)	Medium (1000-3000)	Heavy (3000-6000)	Extra Heavy (greater than 6000)
Stability, min.	330	440	550	660
Flow (0.01 in.)	4-20	4-18	4-16	4-14
Percent air voids	2-15	2-15	3-12	3-10

[after Zoepf as cited in (37)]

TABLE 30

MARSHALL MIX DESIGN CRITERIA FOR

CUTBACK AND EMULSIFIED ASPHALT MIXTURES

Marshall Test	Criteria for a Test Temperature of 77°F	
	Minimum	Maximum
Stability, lbs.	750	---
Flow, (0.01 in.)	7	16
Percent air voids	3	5

[after Lefebvre (49)]

strength of asphalt-aggregate mixtures. A durability test should also be considered to evaluate these mixtures. Tests which could be used to measure durability include the immersion-compression test (13), the swell test (36) and the Moisture Vapor Susceptibility (MVS) test (24).

Numerous laboratory tests have been used to determine asphalt contents for cutback and emulsified asphalts. These methods include:

1. Hubbard-Field Test, ASTM D1138-52 (45)
2. Hveem Stability, ASTM D1560-65 (46, 47)
3. Marshall Stability, ASTM D1559-65 (46, 48, 49)
4. Florida Bearing Test (50)
5. Iowa Bearing Test (51)
6. Extrusion Test, ASTM D915-61 (30, 46)
7. Unconfined Compression Test (45, 46, 52, 53, 54, 55)
8. Triaxial Compression Test (45)
9. "R" Value (20, 56, 57)
10. Elastic Modulus (20, 43, 57)

Mixing methods, curing conditions, rate of loading, and temperature are important variables that must be carefully controlled when the above mentioned tests are performed.

The most promising tests for utilization by the Air Force include the Marshall, Hveem and Extrusion tests. Criteria for the Marshall and Hveem tests have been developed by several investigators and are shown in Tables 30 and 31, respectively. The Air Force is presently recommending use of the Extrusion Test (30) for mixture design with the following criteria used for acceptability:

1. extrusion value before absorption - 1000 lbs. minimum
2. extrusion value after absorption - 400 lbs. minimum

TABLE 31

HVEEM MIX DESIGN CRITERIA

EMULSIFIED ASPHALT MIXTURES

Reference	Criteria		
	Resistance Value		Moisture Pickup
	Before MVS*	After MVS*	During MVS, per cent
Asphalt Institute (19)	70 min.	60 min.	---
Chevron Asphalt Company (20)	---	70**, 78***	5.0 max.
Finn, et al. (57)	---	70**, 73***	5.0 max.

*Moisture Vapor Susceptibility
**Light Traffic
***Heavy Traffic

TABLE 32

SELECTION OF A SUITABLE TYPE OF BITUMEN

FOR SOIL STABILIZATION PURPOSES

Sand Bitumen	Soil Bitumen	Crushed Stones and Sand-Gravel-Bitumen
Hot Mix: Asphalt Cements 60-70 hot climate 85-100 120-150 cold climate		Hot Mix: Asphalt Cements 40-50 hot climate 60-70 85-100 cold climate
Cold Mix: Cutbacks See Figure 9	Cold Mix: Cutbacks See Figure 9	Cold Mix: Cutbacks See Figure 9
Emulsions See Table 19 See Figures 10 and 11 to determine if a catonic or anonic emulsion should be used	Emulsions See Table 19 See Figures 10 and 11 to determine if a catonic or anonic emulsion should be used	Emulsions See Table 19 See Figures 10 and 11 to determine if a catonic or anonic emulsion should be used

3. expansion during absorption test - 5 percent maximum

The unconfined compression test is easy to perform, but sufficient experience to determine adequate criteria for its use is not available.

c. Methods based on combination of laboratory tests on soil and soil-asphalt mixture

In these methods, selection of the quantity of bitumen for stabilization is usually based on preliminary estimates gained by performing tests on the soil. One example is the Hveem method used in California and several western states. Preliminary asphalt content is based on CKE tests, and the final asphalt content is selected on the basis of tests with the Hveem Stabilometer.

Finally, it should be mentioned that the use of elastic modulus for the determination of asphalt content and as input for pavement design has been suggested by Terrel and Monismith (43), Finn et al. (57) and Kari (58). Pavements have been designed using these methods, and the Air Force should give consideration to this testing method since research in pavement design being conducted by the Air Force requires these inputs.

4. Methods of Evaluating Bitumen-Soil Mixtures

The methods used for evaluating bituminous soil mixtures are identical to those used to select the asphalt content. It is important to note that not only are strength or stability criteria necessary, but also durability criteria are recommended by most agencies. Typical examples of these tests are the immersion-compression test utilized by Winterkorn (14) and by Riley and Blomquist (55), and the MVS test utilized by the Chevron Asphalt Company (20), the Asphalt Institute (56) and Finn et al. (57).

5. Summary of Criteria for Bituminous Stabilization Subsystem

Criteria for the bituminous stabilization subsystem of the expedient and nonexpedient soil stabilization index system are given below:

I. Expedient construction

A. Subgrade

1. Selection of bitumen type

a. Do not use asphalt cements
b. From the gradation of the soil determine if a soil bitumen, sand bitumen, crushed stone bitumen, or sand-gravel bitumen (Table 7) can be constructed
c. Use Table 32 to select the type of asphalt

2. Selection of the quantity of bitumen

a. For cutback asphalts use the following equation recommended by the Asphalt Institute (16) and the Navy (22):

$$p = 0.02\ (a) + 0.07\ (b) + 0.15\ (c) + 0.20\ (d)$$

where:

p = percent of residual asphalt by weight of dry aggregate
a = percent of mineral aggregate retained on No. 50 sieve
b = percent of mineral passing No. 50 and retained on No. 100 sieve
c = percent of mineral aggregate passing No. 100 and retained on No. 200 sieve
d = percent of mineral aggregate passing No. 200 sieve

b. For emulsions use Table 24 suggested by the Navy (22)

3. Method of evaluating mixtures

No testing is required

B. Base course

1. Selection of bitumen type

a. From the gradation of the soil determine if a soil bitumen, sand bitumen, crushed stone bitumen, or sand-gravel bitumen (Table 7) can be constructed
b. Use Table 32 to select the type of asphalt

2. Selection of the quantity of bitumen

TABLE 33

SELECTION OF ASPHALT CEMENT CONTENT

FOR EXPEDIENT BASE COURSE CONSTRUCTION

Aggregate Shape and Surface Texture	Percent Asphalt by Weight of Dry Aggregate*
Rounded and Smooth	4
Angular and Rough	6
Intermediate	5

*Approximate quantities which may be adjusted in field based on observation of mix and engineering judgment

TABLE 34

DETERMINATION OF ASPHALT GRADE FOR

BASE COURSE STABILIZATION

Pavement Temperature Index*	Asphalt Grade, Penetration
Negative	100-120
0-40	85-100
40-100	60-70
Above 100	40-50

*The sum, for a 1- year period, of the increments above 75°F of monthly averages of the daily maximum temperatures. Average daily maximum temperatures for the period of record should be used where 10 or more years of record are available. For records of less than 10-year duration the record for the hottest year should be used. A negative index results when no monthly average exceeds 75°F. Negative indexes are evaluated merely by subtracting the largest monthly average from 75°F.

TABLE 35

DETERMINATION OF QUANTITY OF CUTBACK ASPHALT

$$p = 0.02\,(a) + 0.07\,(b) + 0.15\,(c) + 0.20\,(d)$$

where: p = percent of residual asphalt by weight of dry aggregate.

a = percent of mineral aggregate retained on No. 50 sieve.

b = percent of mineral aggregate passing No. 50 and retained on No. 100 sieve.

c = percent of mineral aggregate passing No. 100 and retained on No. 200 sieve.

d = percent of mineral aggregate passing No. 200 sieve.

a. For cutback asphalts use equation recommended by the Asphalt Institute (16) and the Navy (22) given above
b. For emulsions use Table 24 suggested by the Navy (22)
c. For asphalt cement use Table 33

3. Method of evaluating mixtures

No testing is required

II. Nonexpedient construction

A. Subgrade

1. Selection of bitumen type

a. Do not use asphalt cement (if asphalt cement is to be used a hot-plant must be available and usually a base course rather than a subgrade is constructed)
b. From the gradation of the soil determine if a soil bitumen, sand bitumen, crushed stone bitumen or sand-gravel bitumen can be constructed
c. Use Table 32 to select the type of asphalt

2. Selection of the quantity of bitumen

a. For cutback asphalts use the following recommended by the Asphalt Institute (16) and the Navy (22) for a preliminary estimate:

$$p = 0.02\ (a) + 0.07\ (b) + 0.15\ (c) + 0.20\ (d)$$

where:

p = percent of residual asphalt by weight of dry aggregate
a = percent of mineral aggregate retained on No. 50 sieve
b = percent of mineral aggregate passing No. 50 and retained on No. 100 sieve
c = percent of mineral aggregate passing No. 100 and retained on No. 200 sieve
d = percent of mineral aggregate passing No. 200 sieve

Use criteria developed by Lefebvre (Table 30) (49) for final selection of cutback content
b. For emulsion use Table 24 suggested by the Navy for preliminary selection. For final selection use criteria developed by Lefebvre (Table 30) (49). (Note that Lefebvre did not intend these criteria to be used on emulsified asphalt treated soils.)

3. Method of evaluating mixtures

Use tests required above together with a suitable durability test. A suitable durability test or

criteria has not been selected

B. Base course

1. Selection of bitumen type

   a. From the gradation of the soil determine if a soil bitumen, sand bitumen, crushed stone bitumen, or sand-gravel bitumen can be constructed
   b. Use Table 32 to select the type of asphalt

2. Selection of the quantity of bitumen

   a. For cutback asphalts use equation recommended by the Asphalt Institute (16) and the Navy (22) given above for preliminary estimate. Use criteria developed by Lefebvre (Table 30) (49) for final selection of cutback content
   b. For emulsion use Table 24 suggested by the Navy for preliminary selection. For final selection use criteria developed by Lefebvre (Table 30) (49)
   c. For asphalt cements use Table 33 on a preliminary basis. Use criteria developed by the Corps of Engineers for binder course (Table 26) (2) for final selection of asphalt content

3. Methods of evaluating mixtures

   Use tests required above together with a suitable durability test. A suitable durability test or criteria has not been selected.

An effort has been made in the selection of the above criteria to conform to existing test methods and testing apparatus that the Air Force is using on a routine basis. It is felt that more experience has been obtained with the Hveem test method than others, but the Air Force does not possess this equipment. The Asphalt Institute (56) and Chevron Asphalt Company (20), among others, have extensive field data on mixtures designed with Hveem test criteria as given in Tables 25, 28 and 31. For this reason, as well as the inclusion of a durability test (MVS), the Air Force should consider this mixture design method for possible future use. Additionally, the utilization of the elastic modulus for pavement and mixture design should be considered.

The above mentioned criteria have been used for the preparation of the

Bituminous Stabilization Subsystems for Expedient and Nonexpedient Construction operations shown in Figures 12, 13, 14 and 15, respectively.

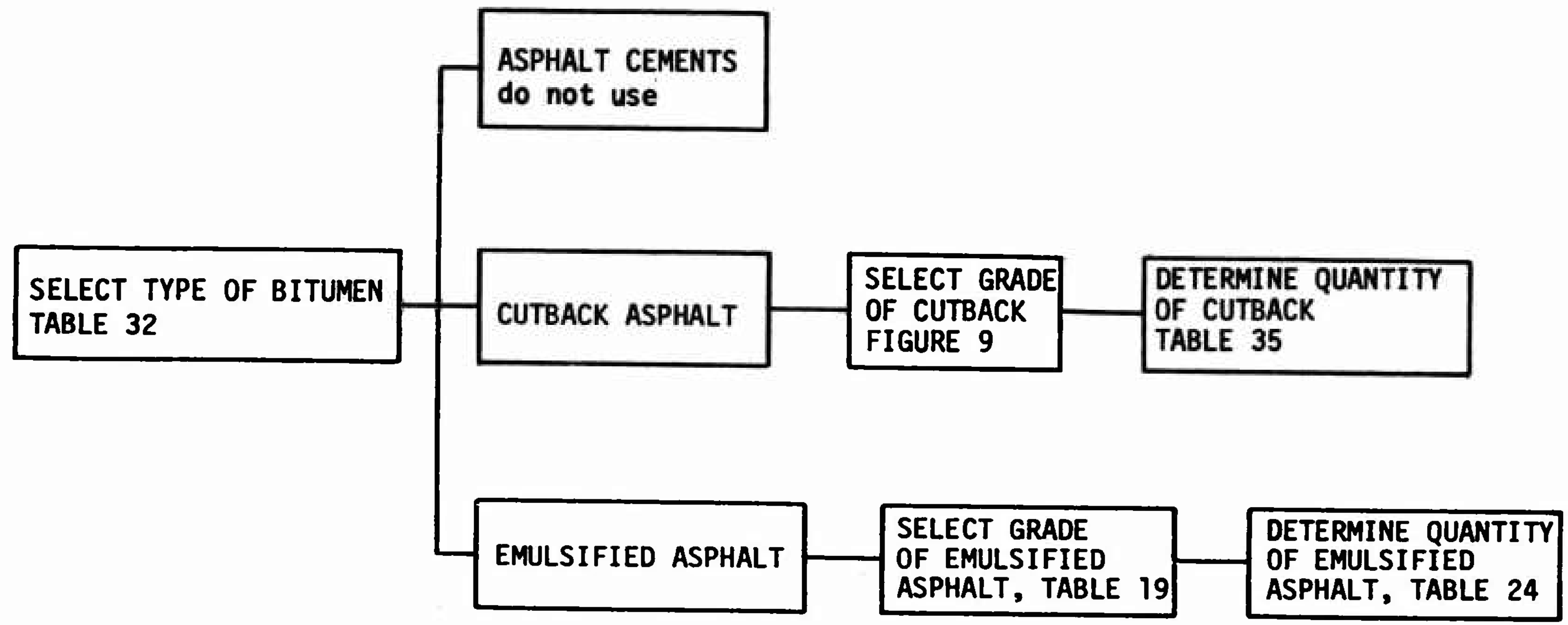


FIGURE 12. SUBSYSTEM FOR EXPEDIENT SUBGRADE STABILIZATION WITH BITUMINOUS MATERIALS

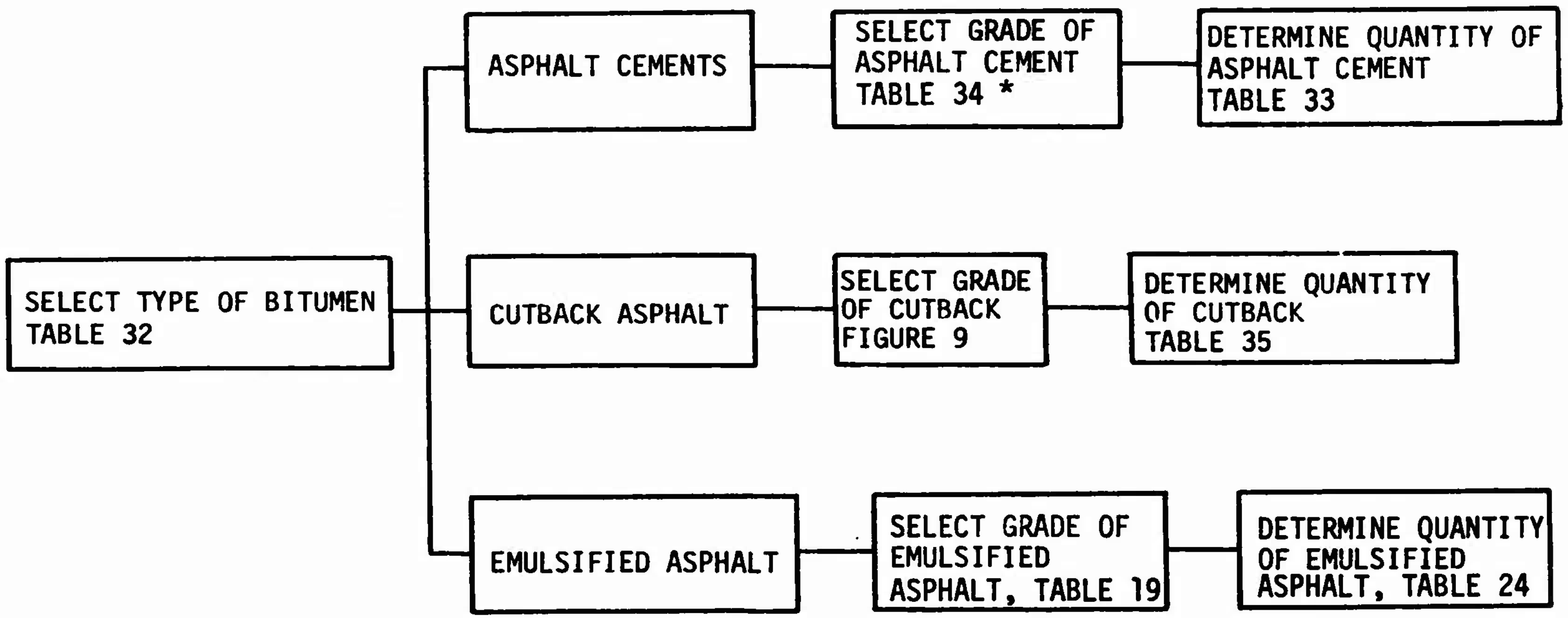


FIGURE 13. SUBSYSTEM FOR EXPEDIENT BASE COURSE STABILIZATION WITH BITUMINOUS MATERIALS

*HARD ASPHALT CEMENTS ARE PREFERRED IN HOT CLIMATES.

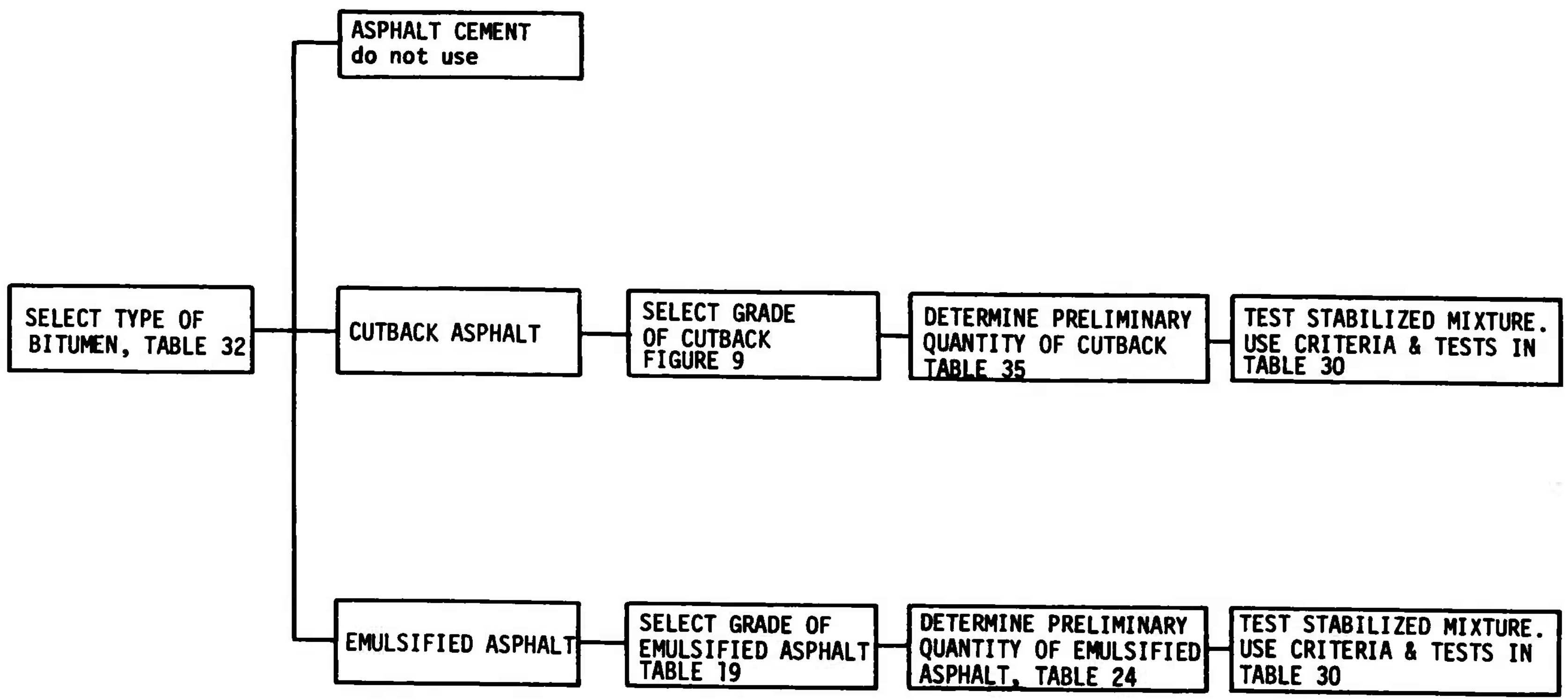


FIGURE 14. SUBSYSTEM FOR NON-EXPEDIENT SUBGRADE STABILIZATION WITH BITUMINOUS MATERIALS

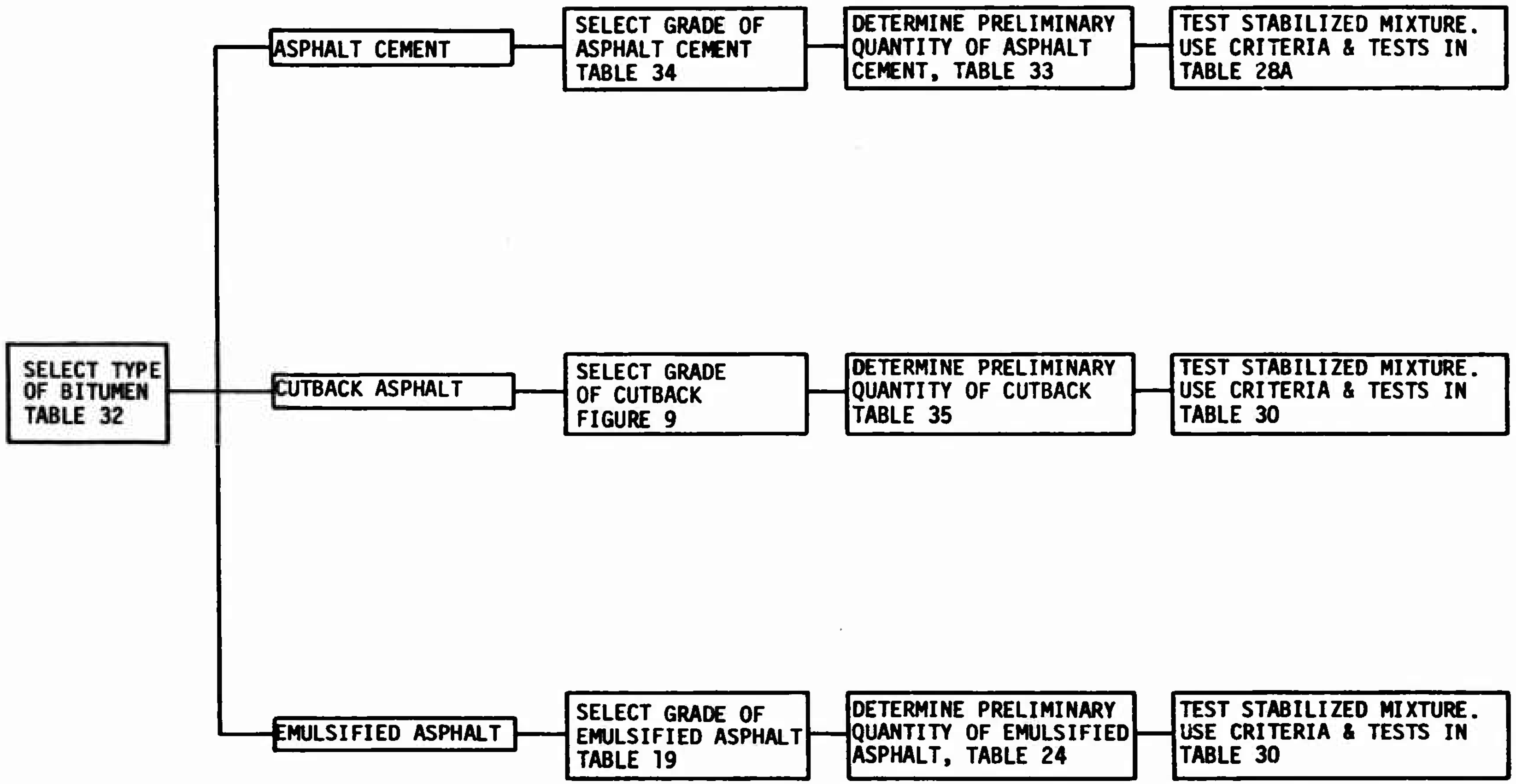


FIGURE 15. SUBSYSTEM FOR NON-EXPEDIENT BASE COURSE STABILIZATION WITH BITUMINOUS MATERIALS

SECTION V

DESIGN SUBSYSTEM FOR PORTLAND CEMENT STABILIZATION

1. Introduction

Numerous technical papers and construction guides have been published on portland cement stabilization (see reference 59, for example). These papers contain criteria which will be reviewed in this section of the report in order to develop the design subsystem for cement stabilization. For convenience these criteria are separated into the following categories:

a. selection of appropriate soils

b. selection of the type of cement

c. selection of the quantity of cement

d. methods of evaluating soil-cement mixtures

These criteria are discussed below.

2. Selection of Appropriate Soils

Information as to general requirements such as gradation and plasticity index have been discussed previously. Most research and construction with soil-cement mixtures has been performed on soils which have been classified according to the AASHO Classification System. Experience has shown that this approach gives good results, but it does not include the important soil properties such as clay type, soil pH, organic content and soil sulfate content that may influence the suitability of a soil for cement stabilization.

Research conducted by the Road Research Laboratory (60) (Figure 16) has indicated a general trend of increased unconfined compressive strength with increased soil pH. For soils with a pH value greater than 7, no ill effects on strength were noted. (Research conducted by Thompson (61) has indicated that a minimum soil pH of 7 is also desirable for lime stabilization.)

Research has been conducted by the Portland Cement Association (62, 63) on the utilization of the standard colorimetric test for the identification of organics, and the pH test on soils to indicate the reactivity of soil and cement. No satisfactory correlation was found. The calcium adsorption test, however, (62) is adequate to determine the presence of organics in sandy soils. MacLean and Sherwood (60) also indicated that the calcium adsorption test was suitable for sandy soils, but that it was unsuitable for clay soils. This opinion is shared by the Portland Cement Association (63).

A satisfactory method for determining the presence of active organic matter is a pH test conducted on a soil-cement paste (10:1 mixture) after 15 minutes. Normal hardening of soil-cement will not occur if the pH of the soil-cement paste has a value below 12 (60). The pH test on the soil-cement mixture is intended to determine the reactivity of a soil with cement. This reactivity is not solely a function of the organic content (62, 64), but it is also dependent upon the types of organics (65). It should be realized that the pH tests performed by the Portland Cement Association (63) were conducted on the soil and not the soil-cement mixture, and therefore extensive data on the latter test are not available.

Sulfates present in the soils and the waters which may come in contact with soil-cement mixtures have a detrimental effect on soil-cement strength. Studies conducted by Sherwood (66) have indicated that sulfate contents in

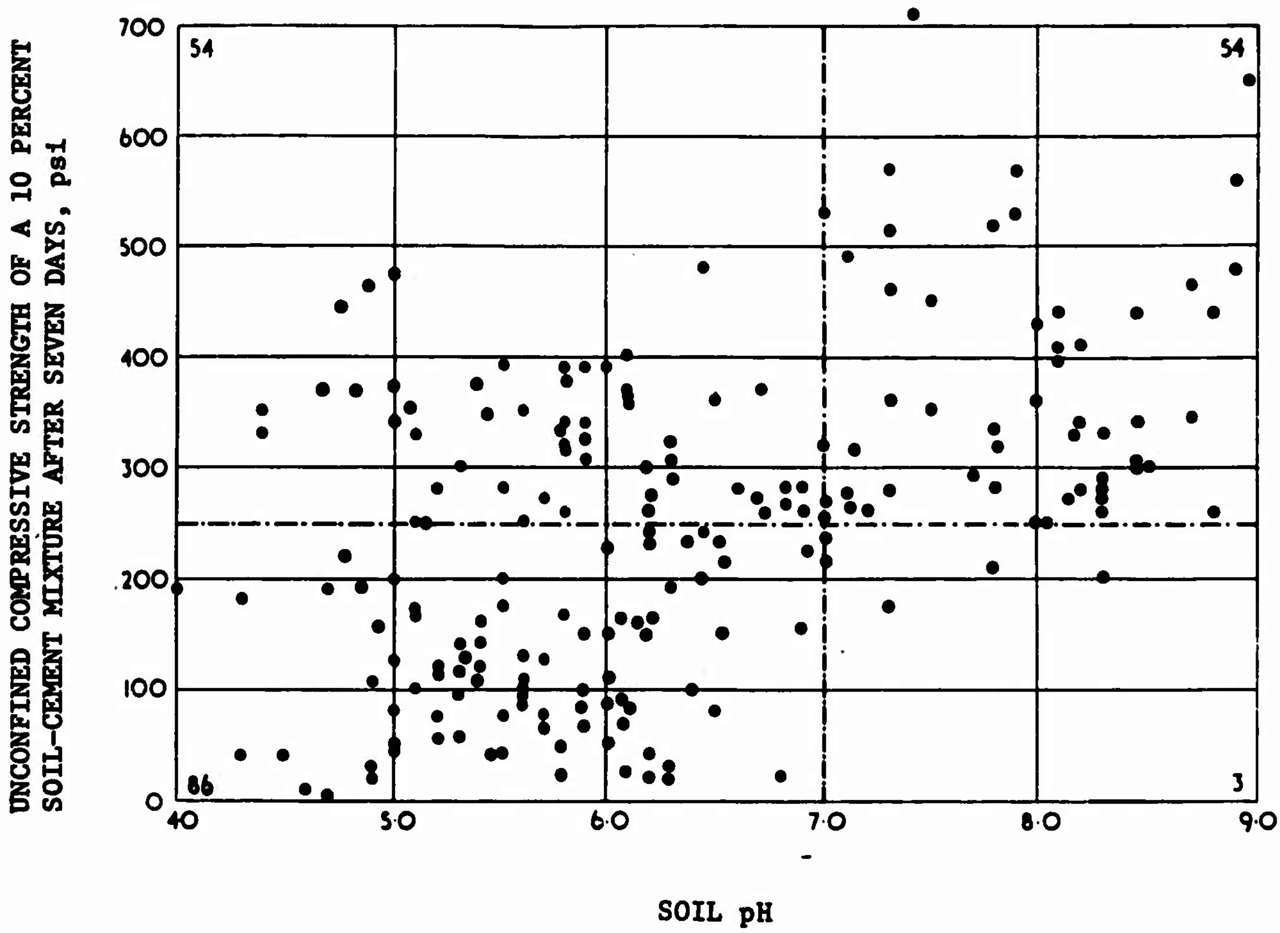


FIGURE 16. Effect of soil pH value on the unconfined compressive strength of soil cement mixtures

[after MacLean and Sherwood (60)]

soils in excess of 0.5 to 1.0 percent reduce the strength of soil-cement mixtures. Similarly, soil-cement mixtures immersed in water containing sulfate concentrations exceeding 0.2 percent resulted in strength loss.

3. Selection of the Type of Cement

The influence of the type of cement on the properties of soil-cement mixtures has been examined by several investigators (66, 67, 68, 69). These studies indicate that only small differences can be expected between Types I, II, III and V cements for most soils. Thus, it is recommended that Type I cement be routinely used for soil-cement. However, if it is not available and other types are, they may be used with no detrimental effects expected. Specifications for cements are given in Table 36 (70).

4. Selection of the Quantity of Cement

Research performed by the Portland Cement Association, presented in Highway Research Board publications (71, 72, 73) and summarized in the Soil-Cement Laboratory Handbook (10), sets forth data for use in determining cement contents for various types of soils. These cement requirements are based on tests performed on over two thousand soils (10), and therefore should be considered to be reliable.

The cement requirements for subsurface soils can be obtained from Table 37. These criteria are based on the AASHO Classification System, but the Air Force has converted this classification for their use as shown in this table.

Requirements for soils in various horizons are also specified by the Portland Cement Association (Tables 37, 38 and 39). It should be noted that estimates of cement content for B and C horizon soils are dependent upon the

TABLE 36

SPECIFICATIONS FOR PORTLAND CEMENT

Physical Requirements	Type I	Type II	Type III	Type IV	Type V
Fineness specific surface, sq cm per g (alternate methods):					
Turbidimeter test:					
Average value, min.	1600	1600	----	1600	1600
Minimum value, any one sample	1500	1500	----	1500	1500
Air permeability test:					
Average value, min	2800	2800	----	2800	2800
Minimum value, any one sample	2600	2600	----	2600	2600
Soundness:					
Autoclave expansion, max, percent	0.80	0.80	0.80	0.80	0.80
Time of setting (alternate methods):					
Gillmore test:					
Initial set, min, not less than	60	60	60	60	60
Final set, hr, not more than	10	10	10	10	10
Vicat test (Method C 191):					
Set, min, not less than	45	45	45	45	45
Air content of mortar, prepared and tested in accordance with Method C 185, max, percent by volume, less than	12.0	12.0	12.0	12.0	12.0
Compressive strength, psi:					
The compressive strength of mortar cubes, composed of 1 part cement and 2.75 parts graded standard sand, by weight, prepared and tested in accordance with Method C 109, shall be equal to or higher than the values specified for the ages indicated below:					
1 day in moist air	----	----	1700	----	----
1 day in moist air, 2 days in water	1200	1000	3000	----	----
1 day in moist air, 6 days in water	2100	1800	----	800	1500
1 day in moist air, 27 days in water	3500	3500	----	2000	3000
Tensile strength, psi:					
The tensile strength of mortar briquets composed of 1 part cement and e parts standard sand, by weight, prepared and tested in accordance with Method C 190, shall be equal to or higher than the values specified for the ages indicated below:					
1 day in moist air	----	----	275	----	----
1 day in moist air, 2 days in water	150	125	375	----	----
1 day in moist air, 6 days in water	275	250	----	175	250
1 day in moist air, 27 days in water	350	325	----	300	325
Heat of hydration:					
7 days, max, cal per g	----	70	----	----	----
28 days, max, cal per g	----	80	----	----	----

Chemical Requirements	Type I	Type II	Type III	Type IV	Type V
Silicon dioxide (SiO_2), min, percent	----	21.0	----	----	
Aluminum oxide (Al_2O_3), max, percent	----	6.0	----	----	
Ferric oxide (Fe_2O_3), max, percent	----	6.0	----	6.5	
Magnesium oxide (MgO), max, percent	5.0	5.0	5.0	5.0	4.0
Sulfur trioxide (SO_3), max, percent					
When $3CaO{\cdot}Al_2O_3$ is 8 percent or less	2.5	2.5	3.0	2.3	2.3
When $3CaO{\cdot}Al_2O_3$ is more than 8 percent	3.0	----	4.0	----	----
Loss on ignition, max, percent	3.0	3.0	3.0	2.3	3.0
Insoluble residue, max, percent	0.71	0.75	0.75	0.75	0.75
Tricalcium silicate ($3CaO{\cdot}SiO_2$), max, percent	----	----	----	35	----
Dicalcium silicate ($3CaO{\cdot}SiO_2$), max, percent	----	----	----	40	----
Tricalcium aluminate ($3CaO{\cdot}Al_2O_3$), max, percent	----	8	15	7	5
Sum of tricalcium silicate and tricalcium aluminate, max, percent	----	58	----	----	----

[after ASTM (70)]

TABLE 37

CEMENT REQUIREMENTS FOR VARIOUS SOILS

AASHO Soil Classification	Unified Soil Classification*	Usual Range in cement requirement**		Estimated cement content and that used in moisture-density test, percent by weight	Cement contents for wet-dry and freeze-thaw tests, percent by weight
		percent by vol.	percent by wt.		
A-1-a	GW, GP, GM, SW, SP, SM	5- 7	3- 5	5	3- 5- 7
A-1-b	GM, GP, SM, SP	7- 9	5- 8	6	4- 6- 8
A-2	GM, GC, SM, SC	7-10	5- 9	7	5- 7- 9
A-3	SP	8-12	7-11	9	7- 9-11
A-4	CL, ML	8-12	7-12	10	8-10-12
A-5	ML, MH, OH	8-12	8-13	10	8-10-12
A-6	CL, CH	10-14	9-15	12	10-12-14
A-7	OH, MH, CH	10-14	10-16	13	11-13-15

*based on correlation presented by Air Force (2)
**for most A horizon soils the cement should be increased 4 percentage points, if the soil is dark grey to grey, and 6 percentage points if the soil is black.

[after Portland Cement Association (10)]

TABLE 38

AVERAGE CEMENT REQUIREMENTS OF B AND C HORIZON SANDY SOILS

Material retained on No. 4 sieve, per cent	Material smaller than 0.05 mm., per cent	Cement content, per cent by wt.					
		Maximum density, lb. per cu.ft.					
		105–109	110–114	115–119	120–124	125–129	130 or more
0–14	0–19	10	9	8	7	6	5
	20–39	9	8	7	7	5	5
	40–50	11	10	9	8	6	5
15–29	0–19	10	9	8	6	5	5
	20–39	9	8	7	6	6	5
	40–50	12	10	9	8	7	6
30–45	0–19	10	8	7	6	5	5
	20–39	11	9	8	7	6	5
	40–50	12	11	10	9	8	6

[after Portland Cement Association (10)]

TABLE 39

AVERAGE CEMENT REQUIREMENTS OF B AND C HORIZON SILTY CLAYEY SOILS

AASHO group index	Material between 0.05 mm. and 0.005 mm., per cent	Cement content, per cent by wt.						
		Maximum density, lb. per cu.ft.						
		90–94	95–99	100–104	105–109	110–114	115–119	120 or more
0– 3	0–19	12	11	10	8	8	7	7
	20–39	12	11	10	9	8	8	7
	40–59	13	12	11	9	9	8	8
	60 or more	—	—	—	—	—	—	—
4– 7	0–19	13	12	11	9	8	7	7
	20–39	13	12	11	10	9	8	8
	40–59	14	13	12	10	10	9	8
	60 or more	15	14	12	11	10	9	9
8–11	0–19	14	13	11	10	9	8	8
	20–39	15	14	11	10	9	9	9
	40–59	16	14	12	11	10	10	9
	60 or more	17	15	13	11	10	10	10
12–15	0–19	15	14	13	12	11	9	9
	20–39	16	15	13	12	11	10	10
	40–59	17	16	14	12	12	11	10
	60 or more	18	16	14	13	12	11	11
16–20	0–19	17	16	14	13	12	11	10
	20–39	18	17	15	14	13	11	11
	40–59	19	18	15	14	14	12	12
	60 or more	20	19	16	15	14	13	12

[after Portland Cement Association (10)]

density of a soil-cement mixture having a cement content specified in Table 37. Average cement requirements for miscellaneous materials are shown in Table 40.

A systems approach to the determination of cement requirements for soils has been presented by the Portland Cement Association (Figure 17) (73). Since these test methods are based on over 30 years of experience, their adoption (at least in part) into the Air Force stabilization index system is recommended. It should be noted that criteria and test methods exist for small and emergency projects (Figure 17) which would be suitable for the expedient construction practice requirements of the Air Force. Detailed information on this approach can be found in reference 73. The Portland Cement Association methods have been adopted in part by the Navy (75), the Army and the Air Force (2).

An additional short-cut method has been proposed by Diamond and Kinter (76). This method makes use of a correlation between the surface area of a soil measured by the glycerol retention test (77) and the cement requirement. A flow diagram for the proposed use of this method is shown in Figure 18.

5. Methods of Evaluating Soil-Cement Mixtures

Various types of tests have been used to evaluate the properties of soil-cement mixtures (59). These methods include the following:

a. Unconfined Compressive Strength

b. Flexural Strength

c. Modulus of Elasticity

   1. Static in Flexure

   2. Static in Compression

   3. Resonance Modulus

TABLE 40

AVERAGE CEMENT REQUIREMENTS

OF MISCELLANEOUS MATERIALS

Type of miscellaneous material	Estimated cement content and that used in moisture-density test		Cement contents for wet-dry and freeze-thaw tests, per cent by wt.
	per cent by vol.	per cent by wt.	
Shell soils	8	7	5- 7- 9
Limestone screenings	7	5	3- 5- 7
Red dog	9	8	6- 8-10
Shale or disintegrated shale	11	10	8-10-12
Caliche	8	7	5- 7- 9
Cinders	8	8	6- 8-10
Chert	9	8	6- 8-10
Chat	8	7	5- 7- 9
Marl	11	11	9-11-13
Scoria containing material retained on the No. 4 sieve	12	11	9-11-13
Scoria not containing material retained on the No. 4 sieve	8	7	5- 7- 9
Air-cooled slag	9	7	5- 7- 9
Water-cooled slag	10	12	10-12-14

[after Portland Cement Association (10)]

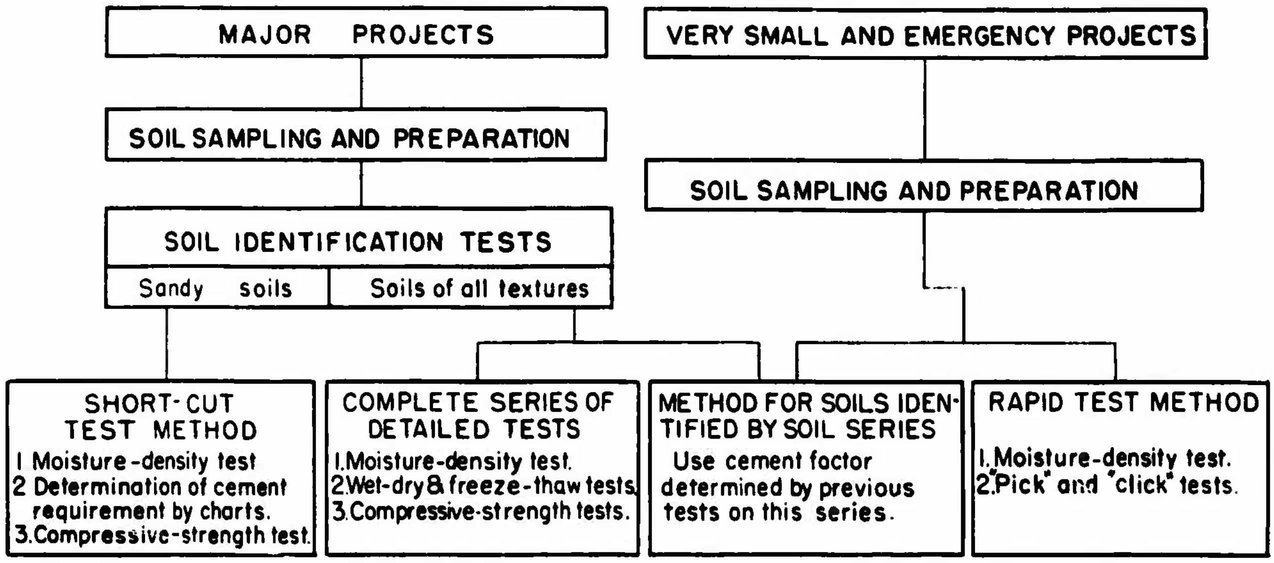


FIGURE 17. SOIL-CEMENT LABORATORY TESTING METHODS

[after Portland Cement Association (74)]

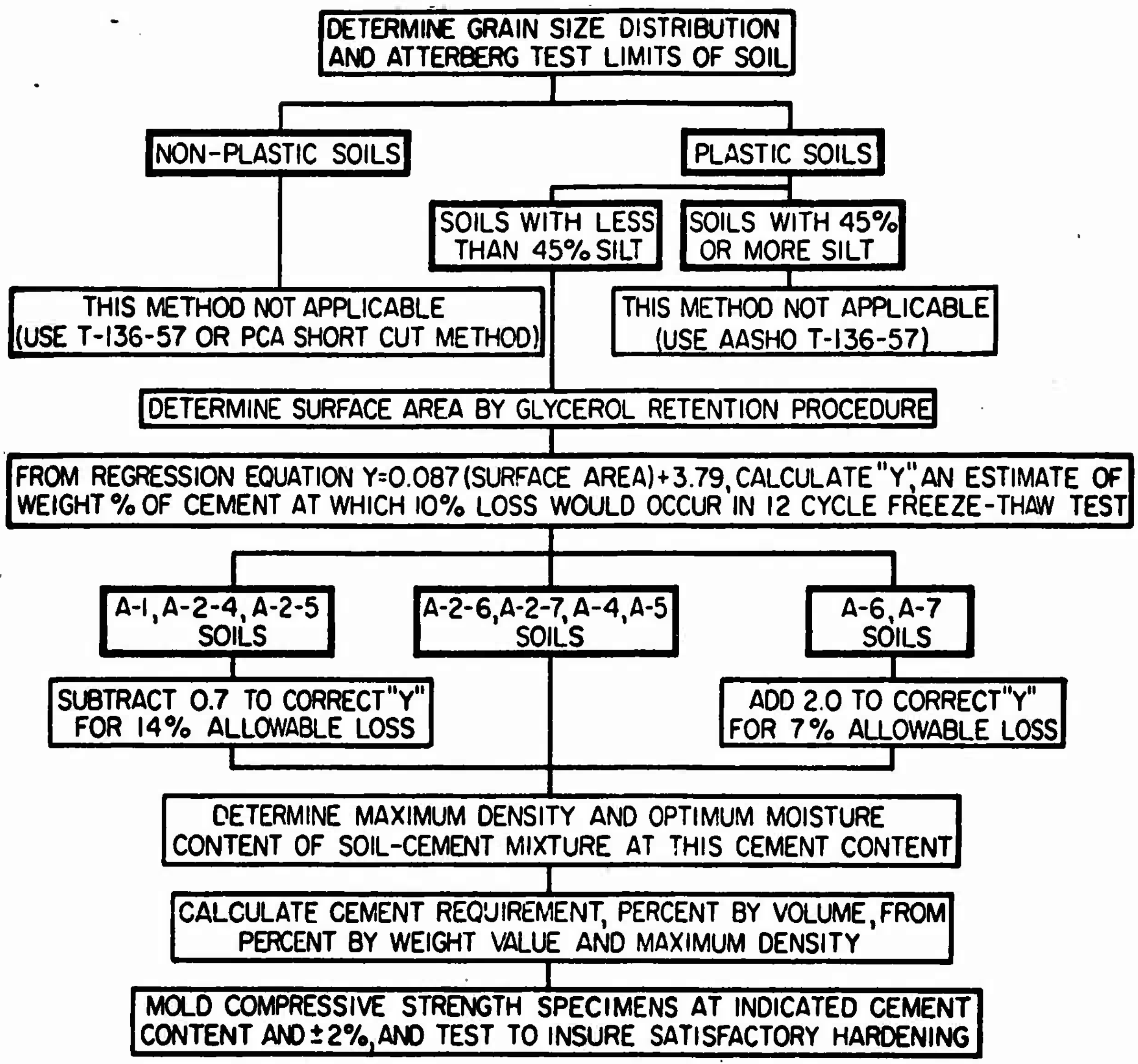


FIGURE 18. Flow diagram for short-cut method using surface area to determine cement requirements

[after Diamond and Kinter (76)]

4. Dynamic

d. California Bearing Ratio

e. Plate Bearing Value

f. Fatigue

g. "R" Value

h. Freeze-Thaw

i. Wet-Dry

Since many of these methods have not been used extensively, satisfactory criteria are not available. However, some tests are being used on a routine basis and criteria have been developed.

Freeze-thaw and wet-dry requirements set forth by the Portland Cement Association (10) are shown in Table 41. These requirements apply to base course construction. It is suggested that freeze-thaw and wet-dry criteria not be used for subgrade stabilization evaluation (63).

Typical unconfined compressive strengths that can be expected for common soil types are shown in Table 42. Unconfined compressive strength criteria used by various agencies are shown in Table 43. The Portland Cement Association specifies minimum compressive strengths for sand-soil-cement mixtures designed by the Short-Cut Methods. These criteria are shown in Figures 19 and 20. These procedures should only be used with soils containing less than 50 percent of particles smaller than 0.05 mm (silt) and less than 20 percent smaller than 0.005 mm (clay).

Criteria dependent on other types of tests are not sufficiently developed to yield reliable data.

6. Summary of Criteria for Cement Stabilization Subsystem

Criteria for the Cement Stabilization Subsystem of the Expedient and

TABLE 41

PORTLAND CEMENT ASSOCIATION CRITERIA FOR

SOIL-CEMENT MIXTURES USED IN BASE COURSES

Soil Classification		Soil-Cement Weight Loss During 12 Cycles of Either Wet-Dry Test or Freeze-Thaw Test
AASHO	Unified*	
A-1 A-2-4, A-2-5 A-3	GW, GP, GM SW, SP, SM GM, GC, SM, SC SP	less than or equal to 14 percent
A-2-6, A-2-7 A-4 A-5	GM, GC, SM, SC CL, ML ML, MH, OH	less than or equal to 10 percent
A-6 A-7	CL, CH OH, MH, CH	less than or equal to 7 percent

*based on correlation presented by Air Force (2)

[after Portland Cement Association (10)]

TABLE 42

RANGES OF UNCONFINED COMPRESSIVE STRENGTHS OF SOIL-CEMENT

Soil Type	Wet Compressive Strength[a] (psi)	
	7-Day	28-Day
Sandy and gravelly soils: AASHO groups A-1, A-2, A-3 Unified groups GW, GC, GP, GF, SW, SC, SP, SF	300-600	400-1,000
Silty soils: AASHO groups A-4 and A-5 Unified groups ML and CL	250-500	300-900
Clayey soils: AASHO groups A-6 and A-7 Unified groups MH and CH	200-400	250-600

[a]Specimens moist cured 7 or 28 days, then saturated in water prior to strength testing.

[after Highway Research Board (59)]

TABLE 43

UNCONFINED COMPRESSIVE STRENGTH CRITERIA FOR SOIL-CEMENT MIXTURES

Agency	Unconfined Compressive Strength, psi	Curing Age, Days
California - Class A&B CTB (ref. 24)	750	7
Texas (ref. 77)	700	7
Road Research Laboratory (ref. 60)	250	7
Air Force (ref. 2)	300	7

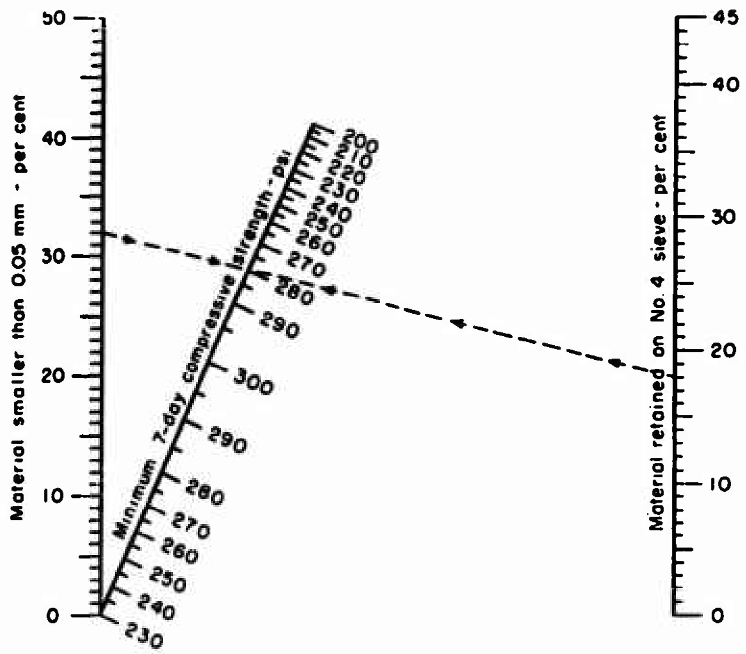


FIGURE 19. Minimum 7-day compressive strengths required for soil-cement mixtures containing material retained on the No. 4 sieve.*

[after Portland Cement Association (10)]

*these strength requirements are applicable provided the soil has the following gradation: <50% smaller than 0.05 mm (silt)
<20% smaller than 0.005 mm (clay)

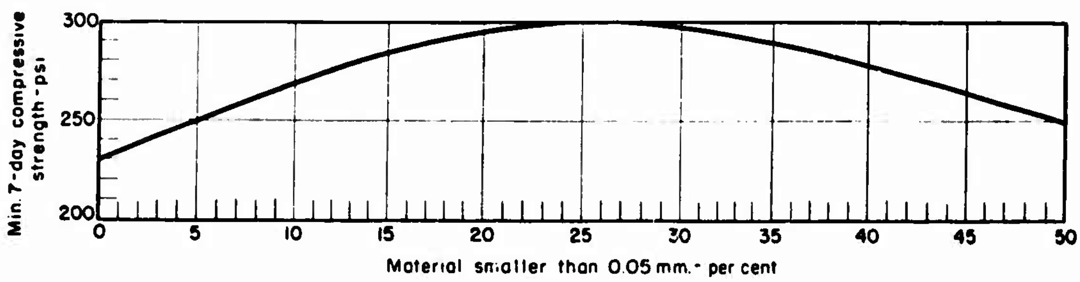


FIGURE 20. Minimum 7-day compressive strengths required for soil-cement mixtures not containing material retained on the No. 4 sieve.*

[after Portland Cement Association (10)]

*these strength requirements are applicable provided the soil has the following gradation: <50% smaller than 0.05 mm (silt)
<20% smaller than 0.005 mm (clay)

Nonexpedient soil stabilization index system are given below.

I. Expedient construction

A. Subgrade

1. Selection of soil type

No additional requirements are recommended

2. Selection of cement type

Use Type I Portland Cement

3. Selection of cement content

Use values selected by Portland Cement Association (Table 37) (10)

4. Methods of evaluating mixtures

Use Rapid Test Procedures recommended by Portland Cement Association (10) shown in Appendix E

B. Base course

These criteria are identical to those listed above for the subgrade

II. Nonexpedient construction

A. Subgrade

1. Selection of soil types

a. Use British test which requires the pH of a 10:1 soil-cement mixture to be 12.0 or greater after 15 minutes (Appendix F)
b. Determine presence of sulfates and require soil to have less than 0.90 percent sulfate content (as SO_4) (Appendix G)

2. Selection of cement type

Use Type I Portland Cemen

3. Selection of cement content

a. If the soil is sandy as defined by the Portland Cement Association, use the short-cut methods recommended by the Portland Cement Association (Appendix H) (10)
b. If the soil is not sandy, use the procedures recommended by Portland Cement Association

(Appendix I) (10), but do not perform the wet-dry and freeze-thaw tests
c. Specimens molded at the selected cement content should pass the "pick" and "click" test given in Appendix E

4. Method of evaluating mixtures

Use those tests required in 3. above

B. Base course

1. Selection of soil types

a. Use British test which requires the pH of a 10:1 soil-cement mixture to be 12.0 or greater after 15 minutes (Appendix F)
b. Determine presence of sulfates and require soil to have less than 0.90 percent sulfate content (as SO_4) (Appendix G)

2. Selection of cement type

Use Type I Portland Cement

3. Selection of cement content

a. If the soil is sandy as defined by the Portland Cement Association, use the short-cut methods recommended by the Portland Cement Association (Appendix H) (10)
b. If the soil is not sandy, use the procedures recommended by Portland Cement Association (Appendix H) (10) and the criteria shown in Table 41 (10)

4. Method of evaluating mixtures

Use those tests required in 3. above

Design subsystems for Expedient and Nonexpedient construction operations are shown in Figures 21, 22, 23 and 24. These subsystems are based on the above criteria.

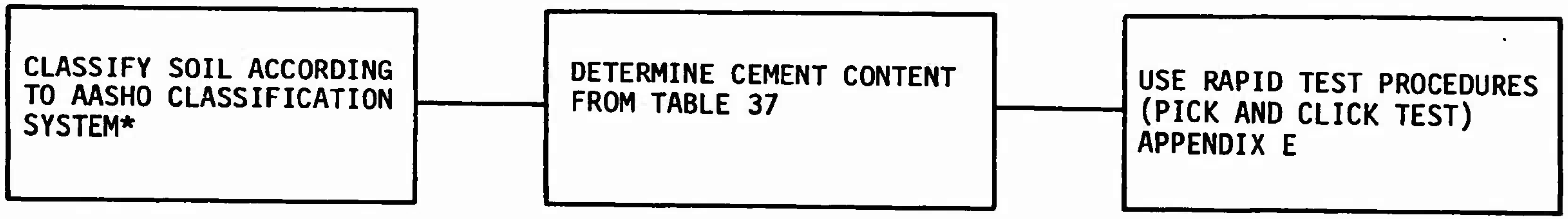


FIGURE 21. SUBSYSTEM FOR EXPEDIENT SUBGRADE STABILIZATION WITH PORTLAND CEMENT

*ALTHOUGH THE UNIFIED CLASSIFICATION SYSTEM CAN BE USED, THE AASHO IS PREFERRED.

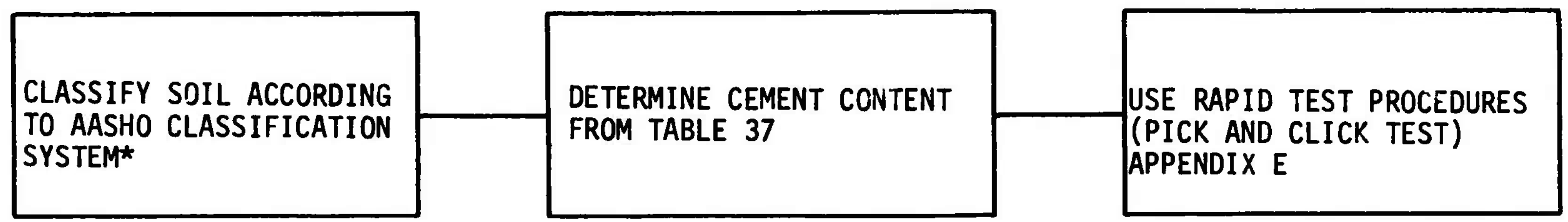


FIGURE 22. SUBSYSTEM FOR EXPEDIENT BASE COURSE STABILIZATION WITH PORTLAND CEMENT

*ALTHOUGH THE UNIFIED CLASSIFICATION SYSTEM CAN BE USED, THE AASHO IS PREFERRED.

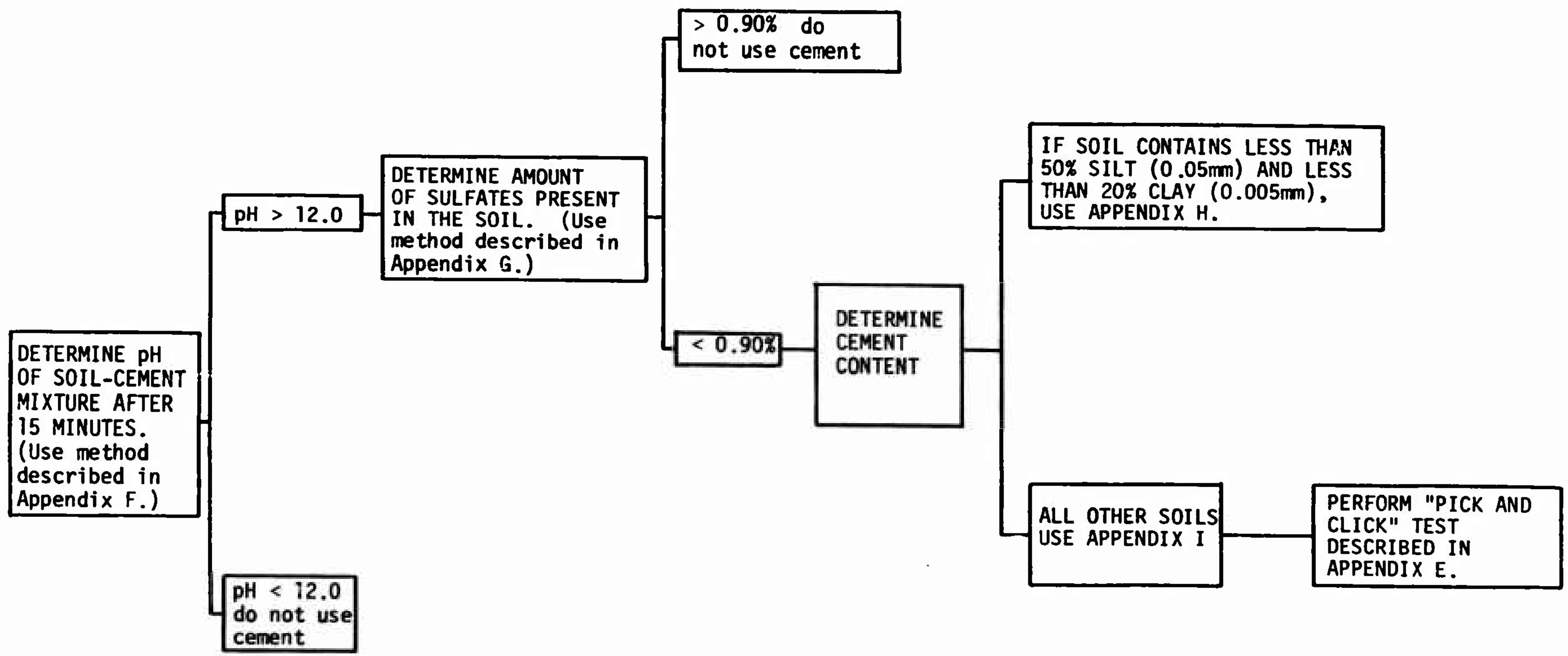


FIGURE 23. SUBSYSTEM FOR NON-EXPEDIENT SUBGRADE STABILIZATION WITH CEMENT

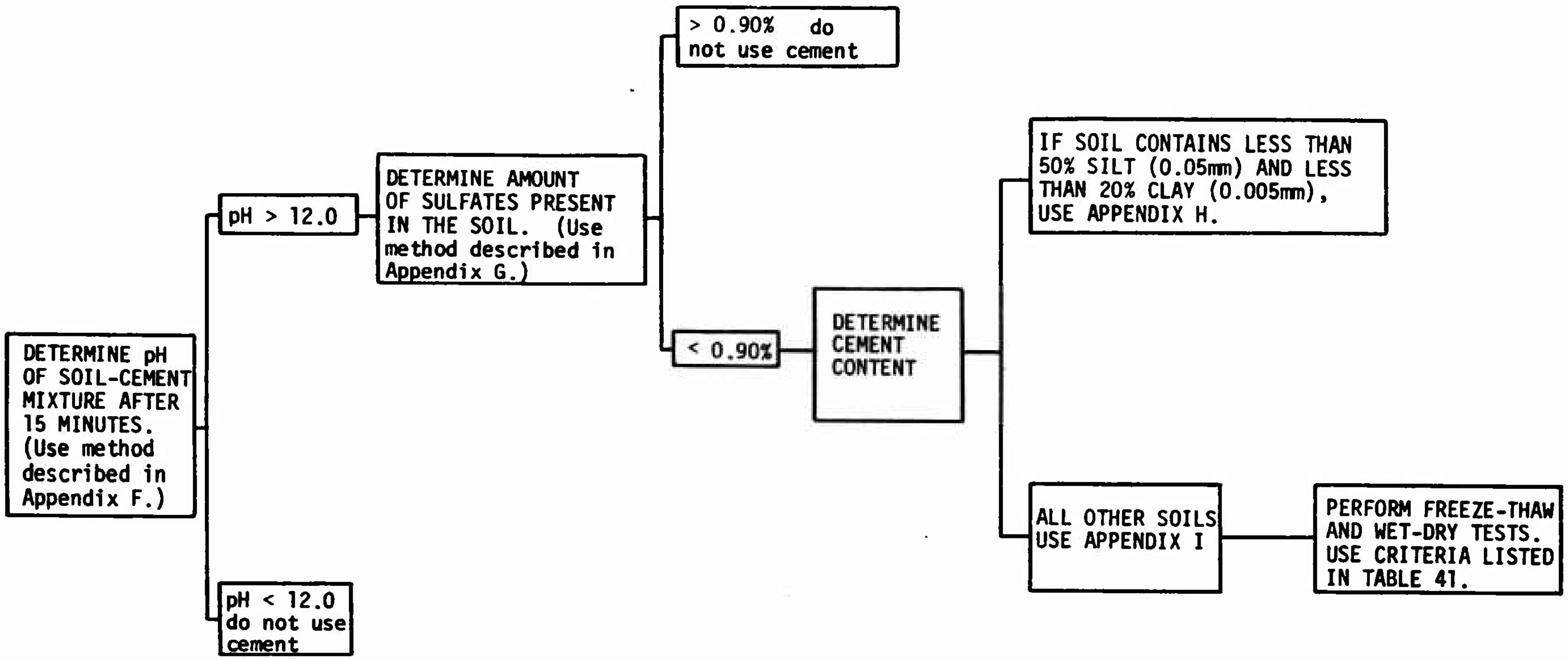


FIGURE 24. SUBSYSTEM FOR NON-EXPEDIENT BASE COURSE STABILIZATION WITH CEMENT

SECTION VI

DESIGN SUBSYSTEM FOR LIME STABILIZATION

1. Introduction

Numerous research publications and technical guides are available on lime stabilization. The wide range of soils successfully stabilized with lime attest to its effectiveness. Numerous criteria have been developed, many of them based on experience with limited soil types. These criteria will be reviewed in this section to develop the lime stabilization subsystem. The following criteria are included:

a. Selection of lime type

b. Selection of appropriate soils

c. Guides to selection of lime quantity

These are discussed below.

2. Selection of Type of Lime

Lime is generally used as an all-encompassing term to denote either slaked (hydrated) lime or quicklime. Also, there are two types of lime: calcitic lime and dolomitic (high magnesium) lime (79, 80). The quality and type of lime are dependent on many factors, including type of stone used, size and gradation of stone, and chemical reactivity of stone, to name a few. There is some disagreement as to whether the type of lime influences the strength of lime-soil mixtures. Some researchers have reported that dolomitic limes produce higher strengths than calcitic limes (81) while others have

found that calcitic limes will produce shear strengths as high as dolomitic limes and may be more desirable for stabilizing certain soil types (82). In the Zone of Interior there may be a choice of limes, in which case it could be economically beneficial to determine which type of lime will be most reactive with the soil. However, in the Theater of Operations, the engineer will use that material which is available without respect to whether it is dolomitic or calcitic, and there is no reason to expect detrimental effects of one over the other.

Lime manufactured in foreign countries may not be as beneficial to soils in the same quantities as U.S. manufactured material. It is not usually subjected to as rigorous a quality control as portland cement or bitumens, and its composition might vary from a single source as well as from different sources. Quality control tests are available (83), but they require equipment not ordinarily available in the Theater of Operations. For these reasons, design tests should be performed using limes from the anticipated sources, and frequent check tests should be made.

Quicklime is reported to have some major advantages over hydrated lime (4):

a. In the treatment of wet soils, strength benefits will occur in a matter of hours,

b. Significant drying effect of the soil will be achieved almost immediately,

c. Less quicklime will be needed than hydrated lime.

However, quicklime can produce severe burns, particularly in hot, humid climates, and adequate safety precautions must be observed.

Hydrated lime may also produce skin irritations.

Specifications for lime which is suitable for stabilization are shown

in Table 44 (84).

3. Selection of Appropriate Soils

Section III discussed the general requirements of the soil with respect to gradation and plasticity. However, there are other requirements which must be considered as well, including organic content of soil, pH, type(s) of clay mineral(s), presence of sulfates and possibly the horizon in which the soil is located.

Thompson (85) has defined soils as being lime-reactive if they display significant strength increase (measured by the unconfined compressive strength) when treated with lime. Soils which are not lime-reactive according to this definition are not necessarily unimproved by the addition of lime as it may still decrease their plasticity, decrease their susceptibility to water, and enhance their overall engineering behavior (86). However, since improved load-bearing characteristics are desired in the stabilization index system, strength will be a major consideration herein.

Soils which have a pH greater than 7 are usually indicative of good lime reactivity (85), although soils with pH values as low as 5.7 have reportedly been effectively stabilized with lime.

It has been reported that soils with organic carbon exceeding about one percent are not satisfactorily lime-reactive (85). And the presence of significant amounts of sulfates also diminishes the effectiveness of lime.

Thompson has reported that A-horizon soils in Illinois do not satisfactorily react with lime (85), and similar reports have been made on other soils; this is probably the result of high organic contents in the upper horizon and the lack of lime reactive constituents. Poorly drained soils often are the most reactive to lime, possibly because of the higher pH and

TABLE 44

SPECIFICATIONS FOR HYDRATED LIME

1. Description. This item establishes the requirements for hydrated lime and commercial lime slurry of the type and grade considered suitable for use in the treatment of natural or processed materials or mixtures for subgrade, subbase and base construction.

2. Types. The various types and grades are defined and identified as follows:

   (1) Type A, Hydrated Lime, shall consist of a dry powder obtained by treating quicklime with enough water to satisfy its chemical affinity for water under the conditions of its hydration. This material is to consist essentially of calcium hydroxide or a small allowable percentage of calcium oxide, magnesium oxide and magnesium hydroxide.

   When sampled and tested according to prescribed procedure, hydrated lime shall conform to the following requirements as to chemical composition:

   Hydrate alkalinity, percent by weight $Ca(OH)_2$ - Min. 90.0%
   Unhydrated lime content, percent by weight CaO - Max. 5.0%
   "Free water" content, percent by weight H_2O - Max. 4.0%

   The percent by weight of residue retained shall conform to the following requirements:

   Residue retained on a No. 6 (3360-micron) sieve - Max. 0.0%
   Residue retained on a No. 10 (2000-micron) sieve - Max. 1.0%
   Residue retained on a No. 30 (590-micron) sieve - Max. 2.5%

   Specifications for Type A apply specifically to the normal hydrate of lime made from "high-calcium" type limestone. Hydrated Lime for stabilization purposes shall be applied, as provided in the governing specifications, as a dry powder or mixed with water to form a slurry.

   (2) Type B, Commercial Lime Slurry, shall be a pumpable suspension of solids in water. The water or liquid portion of the slurry shall not contain dissolved material in sufficient quantity and/or nature injurious or objectionable for the purpose intended. The solids portion of the mixture, when considered on the basis of "solids content," shall consist principally of hydrated lime of a quality and fineness sufficient to meet the following requirements as to chemical composition and residue.

   (a) Chemical Composition. The "solids content" of the lime slurry shall have a hydrate alkalinity $Ca(OH)_2$ of not less than 90 percent by weight.

   (b) Residue. The percent by weight of residue retained in the "solids content" of lime slurry shall conform to the following requirements:

   Residue retained on a No. 6 (3360-micron) sieve - Max. 0.0%
   Residue retained on a No. 10 (2000-micron) sieve - Max. 1.0%
   Residue retained on a No. 30 (590-micron) sieve - Max. 2.5%

   Type B, Commercial Lime Slurry, shall conform to one of the following two grades:

   Grade 1. The "Dry Solids Contents" shall be at least 31 percent by weight of the slurry.

   Grade 2. The "Dry Solids Contents" shall be at least 35 percent by weight of the slurry.

[after Texas Highway Department (84)]

the availability of lime reactive constituents, such as unweathered soil minerals.

In general terms, the soils which are most reactive to lime include

a. Clayey gravels

b. Silty clays

c. Clays.

In the AASHO soil classification system, the most suitable soils include A-2-5, A-2-6, A-2-7, A-5, A-6 and A-7. These correspond generally to the following soils classified by the Unified Soil Classification System: GC, GC-GM, SC, SC-SM, CL, ML, CH, MH. Some lime reactivity may be displayed by GM, SM, and CL-ML soils, and by A-2-4 and A-4 soils.

For the most part, the low plasticity soils do not contain sufficient lime reactive materials to produce significant increases in strength. Thompson (87), however, has reported successful stabilization of some A-4 soils found in Illinois. The use of lime in base courses is not encouraged because of cracking that has occurred in these elements (9). This is probably the result of a certain amount of "tenderness" that occurs in low P.I. lime-stabilized soils. Texas Highway Department experience (88) is that this cracking can be reduced significantly if heavy traffic is kept off the stabilized material for sufficiently long periods of time to allow adequate curing. If a low-type flexible surfacing, such as a surface treatment can be used, then the deleterious effect of cracking will be less serious. Cracking will be reflected in the higher quality surfacings such as hot-mix asphaltic concrete.

In general, the lime stabilized zone will vary with the type of traffic. Lime may be best utilized in expedient construction in the upper layers, particularly if the anticipated traffic is low. In nonexpedient construction, the use of lime will usually be restricted to the lower layers of more plastic

materials where cracking will not be a problem (88).

4. Selection of Lime Quantity

There is less definitive criteria for evaluating the correct quantity of lime than there is for cement or bitumens. Short-cut tests are almost non-existent. As a rough guide the Corps of Engineers (89) has proposed the information given in Table 45 for determining approximate lime contents.

Eades and Grim have proposed a test where the appropriate lime content is that which will produce a pH of a lime-soil mixture of 12.4 one hour after mixing (90). However, recent information has indicated that this test may not be valid for certain highly weathered soils (87).

Most authors have reported that a minimum of 3 percent lime is necessary to produce adequate reactions in the field (86). The Air Force (30) suggests that 2, 3 and 5 percent lime be tried in coarse soils (those containing 50 percent or less passing the No. 200 sieve) while 3, 5 and 7 percent be tried for fine grained soils (greater than 50 percent passing the No. 200 sieve). The National Lime Association recommends the use of 3, 5 and 7 percent lime in trial mixtures (86). With the exception of the pH test described above, the lime content must generally be determined by trial mixtures with the amount of lime being the minimum required to produce the desired reactions.

5. Methods of Evaluating Soil-Lime Mixtures

Several types of tests have been proposed for evaluating soil-lime mixtures. These include, but are not limited to:

a. Unconfined Compressive Strength

b. California Bearing Ratio

c. Flexural Fatigue Strength

TABLE 45

APPROXIMATE LIME CONTENTS

Soil Type	Approximate treatment, percent by soil weight	
	Hydrated Lime	Quicklime
Clayey gravels (GC, GM-GC) (A-2-6, A-2-7)	2-4	2-3
Silty clays (CL) (A-6, A-7-6)	5-10	3-8
Clays (CH) (A-6, A-7-6)	3-8	3-6

[after U. S. Army (89)]

d. Triaxial Compressive Strength

e. Elastic Properties

f. Cohesiometer Values

g. Freeze-thaw Tests

h. Wet-dry Tests.

Most of these tests are not used routinely, and satisfactory criteria are not generally available. Some of the most reliable data are based on unconfined compressive strengths developed from research done by Thompson (91), and presented in Table 46. This table shows strength requirements for various elements in pavements (base course, subbase, etc.) and is based on highway loadings. Until similar data become available for airfield pavements, the values in Table 46 should be considered as minimum values for airfields and should be used with caution.

Durability, the ability of a material to retain stability and integrity over years of exposure to weathering, is perhaps the most difficult to determine. Of the many tests developed, only a modified freeze-thaw test shows substantial merit (92).

6. Summary of Criteria for Lime Stabilization Subsystem

Criteria for the Lime Stabilization Subsystem of the Expedient and Nonexpedient soil stabilization index system are given below.

I. Expedient Construction

A. Subgrade

1. Selection of soil type

No additional requirements recommended.

2. Selection of lime type

Use available lime.

TABLE 46

TENTATIVE LIME-SOIL MIXTURE COMPRESSIVE STRENGTH REQUIREMENTS

Anticipated Use	Residual Strength Requirement, psi (a)	Strength Requirements for Various Anticipated Service Conditions (b)			
			Cyclic Freeze-Thaw (e)		
		Extended (8 day) Soaking (psi)	3 Cycles (psi)	7 Cycles (psi)	10 Cycles (psi)
Modified Subgrade	20	50	50	90 50*	120
Subbase					
Rigid Pavement	20	50	50	90 50*	120
Flexible Pavement					
Thickness of Cover (c)					
10 inches	30	60	60	100 60*	130
8 inches	40	70	70	110 75*	140
5 inches	60	90	90	130 100*	160
Base	100(d)	130	130	170 150*	200

a) Minimum anticipated strength following first winter exposure.

b) Strength required at termination of field curing (following construction) to provide adequate residual strength.

c) Total pavement thickness overlying the subbase. The requirements are based on the Boussinesq stress distribution. Rigid pavement requirements apply if cemented materials are used as base courses.

d) Flexural strength should be considered in thickness design.

e) Number of freeze-thaw cycles expected in the lime-soil layer during the first winter of service.

*Note: Freeze-thaw strength losses based on 10 psi/cycle except for 7 cycle values indicated by an * which were based on a previously established regression equation.

[after Thompson (92)]

3. Selection of lime content

   a. Estimate approximate lime content (Table 45)

   b. Use pH test (Appendix J) on mixtures containing approximate lime contents and require mixture to have pH greater than 12.4 after 1 hour.

4. Methods of evaluating mixture

   No further tests required

B. Base course

1. Selection of soil type

   No additional requirements recommended

2. Selection of lime type

   Use available lime

3. Selection of lime content

   a. Use pH test (Appendix J) on mixtures and determine minimum lime content giving pH of 12.4 after 1 hour.

   b. Mold unconfined compressive strength specimens on mixture with minimum lime content

   c. If lime produces strength increase greater than 50 psi, soil is lime reactive. Mold additional strength specimens at $\pm$ 2 percent lime to obtain optimum lime content.

   d. If lime produces strength increase less than 50 psi, soil is not lime reactive and will not stabilize with lime.

4. Method of evaluating mixture

   Use unconfined compression specimens and compare

with criteria in Table 46.

II. Nonexpedient Construction

A. Subgrade

These requirements are identical to those for expedient base course given above.

B. Base course

These requirements are identical to those for expedient base course given above.

The above criteria were used to develop the lime stabilization subsystems shown in Figures 25, 26, 27 and 28.

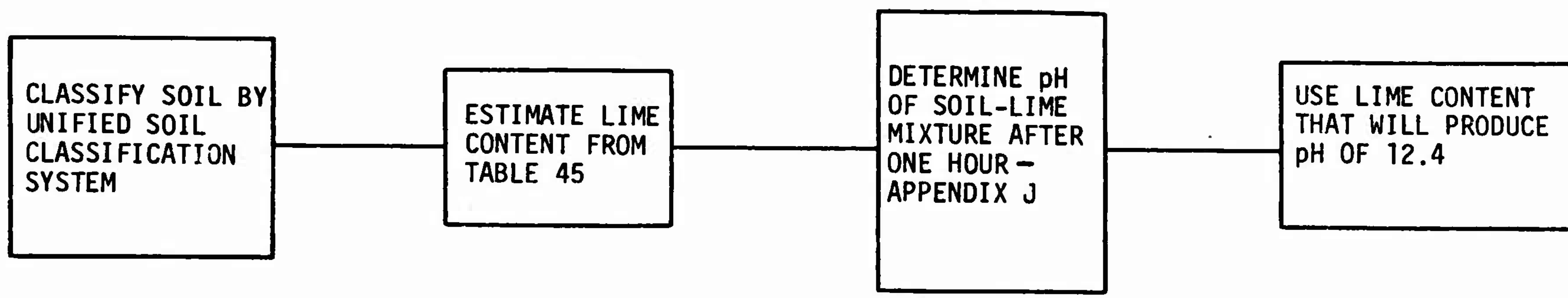


FIGURE 25. SUBSYSTEM FOR EXPEDIENT SUBGRADE STABILIZATION WITH LIME

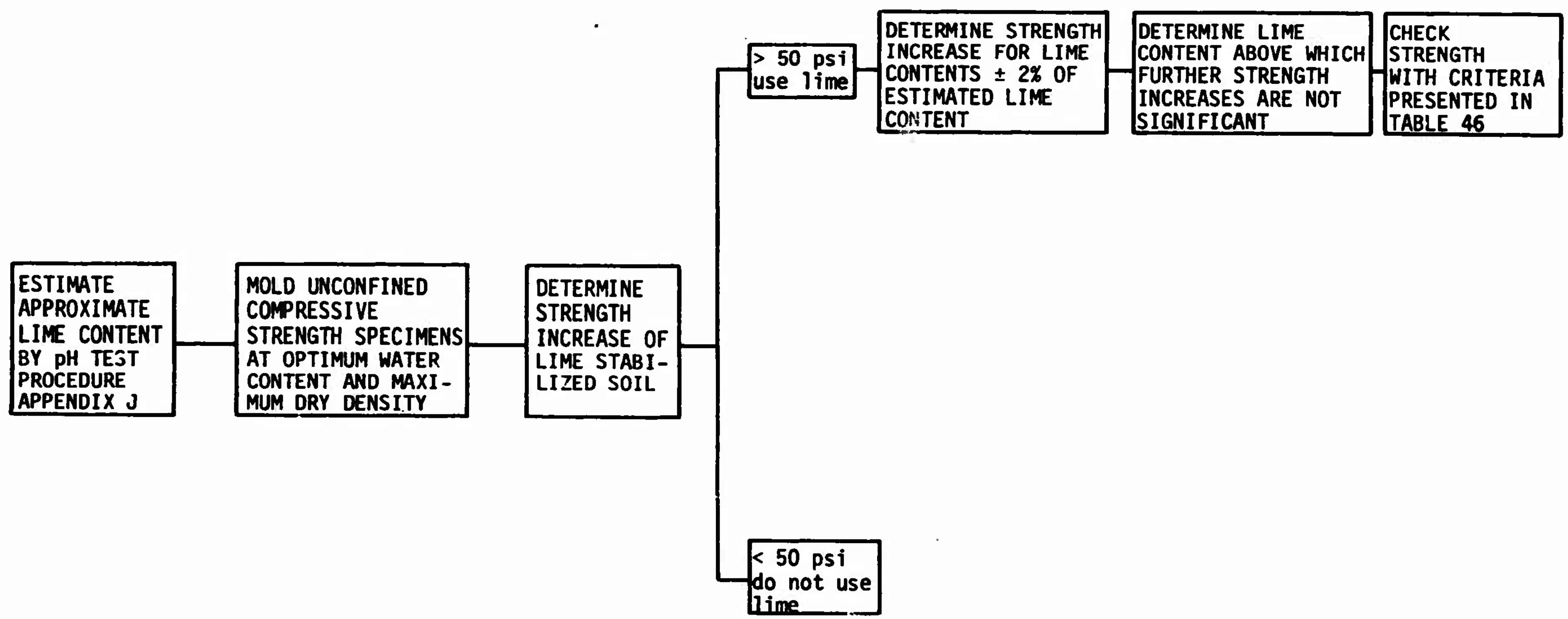


FIGURE 26. SUBSYSTEM FOR EXPEDIENT BASE COURSE STABILIZATION WITH LIME

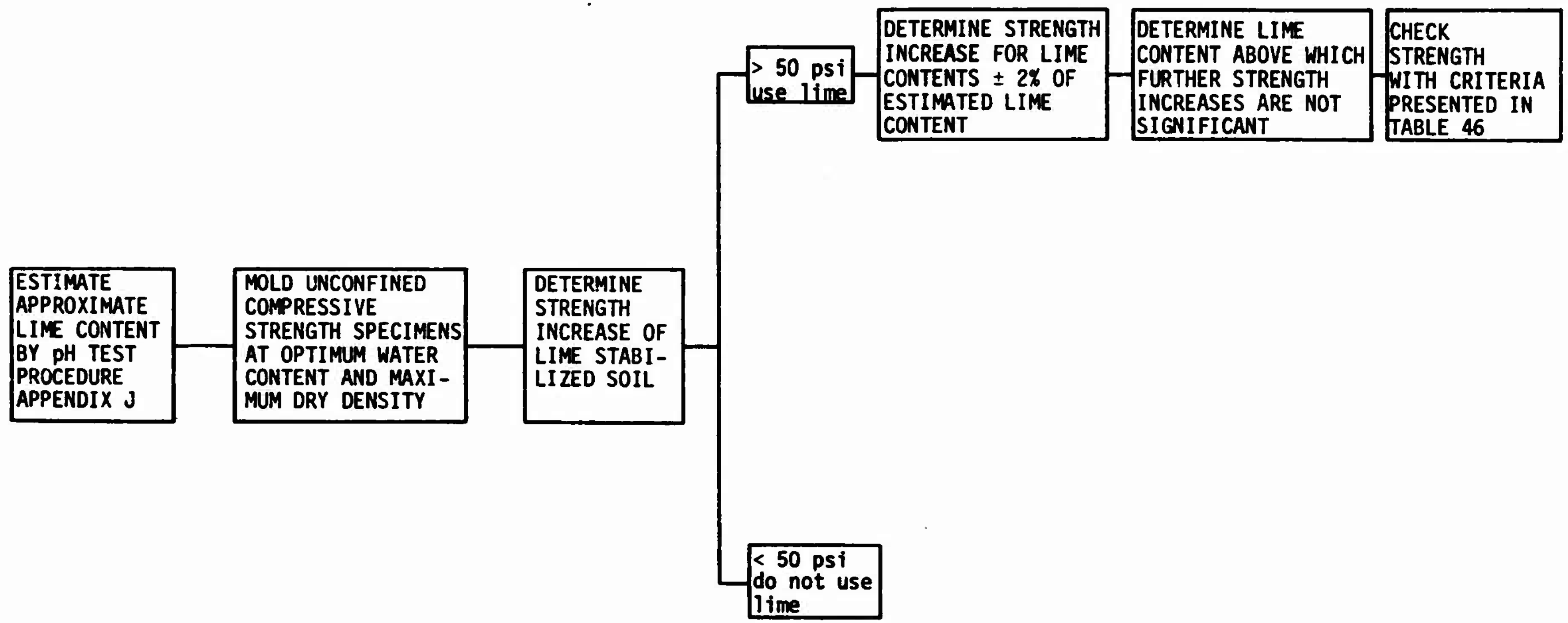


FIGURE 27. SUBSYSTEM FOR NON-EXPEDIENT SUBGRADE STABILIZATION WITH LIME

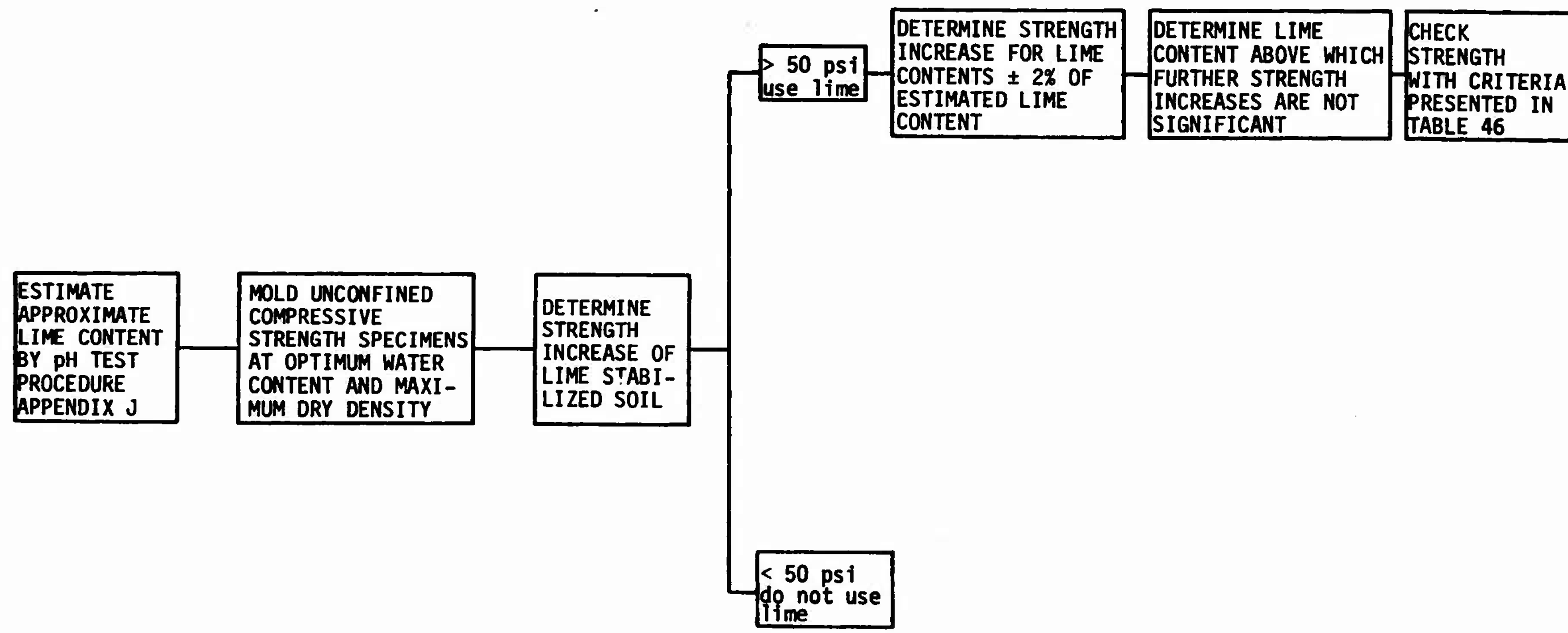


FIGURE 28. SUBSYSTEM FOR NON-EXPEDIENT BASE COURSE STABILIZATION WITH LIME

SECTION VII

SELECTION OF CRITERIA FOR MECHANICAL STABILIZATION

1. Introduction

In recent years, the considerable volume of research on chemical soil stabilization has glamorized this method to the extent that the older stabilization methods are often forgotten. Yet, these older and logistically more appealing methods may do the job as well as chemical stabilization and at a fraction of the cost. The methods being referred to here are densification (compaction) and blending. Both compaction and blending are part of the construction sequence in chemical stabilization, thus much of the basic equipment for the two different methods is identical.

Whether to use chemical or mechanical stabilization is a basic engineering decision where there are no specific guide rules. In all probability, it is the difficulty of making this decision on a quantitative basis that has caused many engineers to turn to chemical stabilization (which seems a more positive method) and neglect mechanical means. It is not purported that this section can provide means for making this decision, but it can provide some of the questions which the engineer should ask when deciding which stabilization method should be used. These are outlined below.

a. Strength

Will mechanical stabilization alone provide adequate strength, or will it be necessary to use chemical additives? Compaction alone can result in strength gains of 300 percent or more. Too often, engineers forget this

fact and search for more sophisticated methods. The magnitude of strength increase available can be determined simply by CBR tests on specimens compacted at various compactive efforts in accordance with procedures outlined in Technical Manuals TM 5-824-2 (25) and TM 5-824-3 (93). However, environmental factors must not be neglected.

b. Permanency of Strength

Will the strength gains by mechanical stabilization be permanent? It is here that the decision for chemical or mechanical stabilization is often made. Many soils will exhibit high strength gains when compacted but they may lose a portion or all of this strength by various means including infiltration of water from the surface or surrounding soil, disrupting action of frost, and others. Information given in Technical Memorandum No. 3-357 by the Waterways Experiment Station (94) (Table 47) gives a very good estimate of the permanency of strength that can be expected with various soils classified according to the Unified Soil Classification System.

In many cases, certain construction procedures can be used to maintain strength or decrease the rate of strength deterioration. For example, a thin asphalt prime coat will impede moisture movement into a the soil, at least from the surface. Enclosing the soil in an impermeable membrane is another means of maintaining the as-built strength. The membrane material may be heavy plastic sheeting, low penetration grades of asphalt cement or a combination of the two, usually with the plastic sheeting on the underside of the enveloped layer and the asphalt cement on the top side. Care must be taken to prevent rips in the plastic or "holidays" in the asphalt cement coating, although for high risk, short life, expedient operations (which this process seems well

TABLE 47. CHARACTERISTICS PERTINENT TO ROADS AND AIRFIELDS

Major Divisions (1)	(2)	Symbol: Letter (3)	Symbol: Hatching (4)	Symbol: Color (5)	Name (6)	Value as Subgrade When Not Subject to Frost Action (7)	Value as Subbase When Not Subject to Frost Action (8)	Value as Base When Not Subject to Frost Action (9)	Potential Frost Action (10)	Compressibility and Expansion (11)	Drainage Characteristics (12)	Compaction Equipment (13)	Unit Dry Weight lb per cu ft (14)	Typical Design Values: CBR (15)	Typical Design Values: Subgrade Modulus k lb per cu in. (16)
COARSE-GRAINED SOILS	GRAVEL AND GRAVELLY SOILS	GW		Red	Well-graded gravels or gravel-sand mixtures, little or no fines	Excellent	Excellent	Good	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller, steel-wheeled roller	125-140	40-80	300-500 *
		GP		Red	Poorly graded gravels or gravel-sand mixtures, little or no fines	Good to excellent	Good	Fair to good	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller, steel-wheeled roller	110-140	30-60	300-500 *
		GM d		Yellow	Silty gravels, gravel-sand-silt mixtures	Good to excellent	Good	Fair to good	Slight to medium	Very slight	Fair to poor	Rubber-tired roller, sheepsfoot roller; close control of moisture	125-145	40-60	300-500 *
		GM u		Yellow		Good	Fair	Poor to not suitable	Slight to medium	Slight	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	115-135	20-30	200-500 *
		GC		Yellow	Clayey gravels, gravel-sand-clay mixtures	Good	Fair	Poor to not suitable	Slight to medium	Slight	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	130-145	20-40	200-500 *
	SAND AND SANDY SOILS	SW		Red	Well-graded sands or gravelly sands, little or no fines	Good	Fair to good	Poor	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller	110-130	20-40	200-400 *
		SP		Red	Poorly graded sands or gravelly sands, little or no fines	Fair to good	Fair	Poor to not suitable	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller	105-135	10-40	150-400 *
		SM d		Yellow	Silty sands, sand-silt mixtures	Fair to good	Fair to good	Poor	Slight to high	Very slight	Fair to poor	Rubber-tired roller, sheepsfoot roller; close control of moisture	120-135	15-40	150-400 *
		SM u		Yellow		Fair	Poor to fair	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	100-130	10-20	100-300 *
		SC		Yellow	Clayey sands, sand-clay mixtures	Poor to fair	Poor	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	100-135	5-20	100-300
FINE-GRAINED SOILS	SILTS AND CLAYS LL IS LESS THAN 50	ML		Green	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	Poor to fair	Not suitable	Not suitable	Medium to very high	Slight to medium	Fair to poor	Rubber-tired roller, sheepsfoot roller; close control of moisture	90-130	15 or less	100-200
		CL		Green	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Poor to fair	Not suitable	Not suitable	Medium to high	Medium	Practically impervious	Rubber-tired roller, sheepsfoot roller	90-130	15 or less	50-150 *
		OL		Green	Organic silts and organic silt-clays of low plasticity	Poor	Not suitable	Not suitable	Medium to high	Medium to high	Poor	Rubber-tired roller, sheepsfoot roller	90-105	5 or less	50-100
	SILTS AND CLAYS LL IS GREATER THAN 50	MH		Blue	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	Poor	Not suitable	Not suitable	Medium to very high	High	Fair to poor	Sheepsfoot roller, rubber-tired roller	80-105	10 or less	50-100
		CH		Blue	Inorganic clays of high plasticity, fat clays	Poor to fair	Not suitable	Not suitable	Medium	High	Practically impervious	Sheepsfoot roller, rubber-tired roller	90-115	15 or less	50-150 *
		OH		Blue	Organic clays of medium to high plasticity, organic silts	Poor to very poor	Not suitable	Not suitable	Medium	High	Practically impervious	Sheepsfoot roller, rubber-tired roller	80-110	5 or less	25-100
HIGHLY ORGANIC SOILS		Pt		Orange	Peat and other highly organic soils	Not suitable	Not suitable	Not suitable	Slight	Very high	Fair to poor	Compaction not practical	-	-	-

Note:

1. Column 3, division of GM and SM groups into subdivisions of d and u are for roads and airfields only. Subdivision is on basis of Atterberg limits; suffix d (e.g., GMd) will be used when the liquid limit is 25 or less and the plasticity index is 5 or less; the suffix u will be used otherwise.
2. In column 13, the equipment listed will usually produce the required densities with a reasonable number of passes when moisture conditions and thickness of lift are properly controlled. In some instances, several types of equipment are listed because variable soil characteristics within a given soil group may require different equipment. In some instances, a combination of two types may be necessary.
   a. Processed base materials and other angular materials. Steel-wheeled and rubber-tired rollers are recommended for hard, angular materials with limited fines or screenings. Rubber-tired equipment is recommended for softer materials subject to degradation.
   b. Finishing. Rubber-tired equipment is recommended for rolling during final shaping operations for most soils and processed materials.
   c. Equipment size. The following sizes of equipment are necessary to assure the high densities required for airfield construction:
      Crawler-type tractor -- total weight in excess of 30,000 lb.
      Rubber-tired equipment -- wheel load in excess of 15,000 lb, wheel loads as high as 40,000 lb may be necessary to obtain the required densities for some materials (based on contact pressure of approximately 65 to 150 psi).
      Sheepsfoot roller -- unit pressure (on 6- to 12-sq-in. foot) to be in excess of 250 psi and unit pressures as high as 650 psi may be necessary to obtain the required densities for some materials. The area of the foot should be at least 5 per cent of the total peripheral area of the drum, using the diameter measured to the faces of the feet.
3. Column 14, unit dry weights are for compacted soil at optimum moisture content for modified AASHO compaction effort.
4. In column 15, the maximum value that can be used in design of airfields is, in some cases, limited by gradation and plasticity requirements.

[after U. S. Army (93)]

* Revised from previous issue.

suited for) this may not be of paramount importance.

c. Construction Weather

Will the climatological conditions be suitable for mechanical stabilization? Often the climate during the construction period will be unsuitable. If the rainfall is too high, then it may be impossible to dry the soil to a moisture content suitable for compaction. Also, low temperatures retard evaporation and make it difficult to obtain the correct moisture.

d. Construction Equipment Limitations

Will the available construction equipment be suitable for mechanical stabilization? The compaction equipment available on the project should be adequate to produce the high densities needed for strength purposes. If not, then the hardening and/or binding effect of chemical stabilizers may be needed. Insofar as blending is concerned, it should be realized that attempts to blend small quantities of soils in the laboratory for experimentation purposes are usually much more successful than in the field. In general, until better mixing equipment becomes available, blending should be used sparingly, and only within the limitations imposed later in this section.

e. Material Logistics

If blending is necessary, will it be feasible, both from an economic and time viewpoint? It may take only 5-7 percent clay to stabilize a sand, whereas 90-95 percent sand may be needed to adequately stabilize a clay. Obviously, the latter would not be feasible even if the sand were nearby.

If the engineer determines that the strength of the mechanically stabilized material will be adequate and of sufficient permanency for the

project at hand, and if the construction weather, construction equipment and material logistics are favorable, then mechanical stabilization may be used, subject to the requirements and limitations discussed below.

2. <u>Compaction Requirements</u>

The Corps of Engineers have developed compaction requirements for subgrades, subbases and base courses. These requirements are based on extensive test track and full scale testing, and can be considered to be the best presently available for airfield construction.

Compaction requirements for subgrades, subbases, and base courses for flexible as well as rigid airfield construction are available in TM 5-824-2 (25) and TM 5-824-3 (93). Various Air Force manuals for airfields, roads, etc., refer to these manuals.

Although the compaction requirements for flexible pavements are more specifically given in TM 5-824-2 as shown in Table 48, a summary of the requirements is presented below:

a. Base Course - excess of 100 percent of Modified AASHO

b. Subbase - 100 percent or greater of Modified AASHO

c. Subgrade

    1. Cohesionless material - 100 percent Modified AASHO

    2. Cohesive material - top portion greater than 95 percent Modified AASHO

d. Fill Sections

    1. Cohesionless materials - 95 percent Modified AASHO

    2. Cohesive materials - 90 percent Modified AASHO

As shown in Table 48 the depth of densification for select material and subgrade is dependent on the type of aircraft, type of materials and density

TABLE 48

COMPACTION REQUIREMENTS

Material	Percentage Compaction
	Materials with Design CBR Values of 20 and above
Base courses	Maximum that can be obtained, generally in excess of 100% of modified AASHO maximum and never less than 100%. Proof-rolling* in Type A traffic areas and central 100 ft of runways for heavy load pavements.
Subbases and subgrades	100% of modified AASHO maximum except where it is known that a higher density can be obtained practicably, in which case the higher density should be required.
	Materials with Design CBR Values below 20
Select material and subgrades in fills	As shown below except that in no case will cohesionless fill be placed at less than 95% nor cohesive fill at less than 90%.
Subgrade in cuts	Subgrade in cuts must have natural densities equal to or greater than the values listed below. Where such is not the case, the subgrade must (a) be compacted from the surface to meet the tabulated densities, (b) be removed and replaced, in which case the requirements given above for fills apply, or (c) be covered with sufficient select material subbase and base so that the uncompacted subgrade is at a depth where the in-place densities are satisfactory.

Depth of Compaction for Select Materials and Subgrades

Type of Assembly	Gear Load kips	Depth of Compaction in Feet for Percent Modified AASHO Compaction Shown: Cohesionless Materials 100 A	B	C	D	95 A	B	C	D	90 A	B	C	D	85 A	B	C	D	Cohesive Materials 100 A	B	C	D	95 A	B	C	D	90 A	B	C	D	85 A	B	C	D	80 A	B	C	D
Heavy Load Pavements																																					
Twin-twin, bicycle	160**		3				5.5				8				10				1.5				3				4				5.5				7		
Spacing, 37-62-37 in. / Contact area, 267 sq in.	265	4.5	4	3.5	2	8	7.5	6.5	4	11.5	10.5	9	5.5	14	13	11	6.5	2.5	2.5	2	1.5	4.5	4	3.5	2	6.5	6	5	3	8.5	8	6.5	4	10.5	9.5	8	4.5
Light Load Pavements																																					
Single wheel	10		1	1			1.5	1.5			2	2			3	2.5			0.5	0.5			1	1			1	1			1.5	1.5			2	1.5	
Contact area, 100 sq in.	20		1.5	1			2	1.5			3	2.5			4	3.5			1	1			1.5	1			1.5	1.5			2	2			2.5	2.5	
	25		1.5	1.5			2.5	2			3.5	3			4	4			1	1			1.5	1.5			2	1.5			2.5	2			3	3	
	30		1.5	1.5			2.5	2.5			4	3.5			4.5	4			1	1			1.5	1.5			2	2			3	2.5			3.5	3	
Miscellaneous																																					
Twin-twin, bicycle	160	3	3	2.5	1.5	6	5.5	4.5	2.5	8.5	8	6.5	4	10.5	10	8	5	2	1.5	1.5	1	3	3	2.5	1.5	4.5	4	3.5	2	6	5.5	5	3	7.5	7	6	3.5
Spacing, 37-62-37 in.	200	3.5	3.5	3	1.5	6.5	6.5	5.5	3	9.5	9	7.5	4.5	12	11	9.5	5.5	2	2	1.5	1	3.5	3.5	3	1.5	5.5	5	4	2.5	7	6.5	5.5	3.5	8	8	7	4
Contact area, 267 sq in.	230	4	4	3	2	7.5	7	6	3.5	10.5	10	8	5	13.5	12.5	10.5	6	2.5	2	2	1	4	4	3	2	6	5.5	4.5	2.5	8	7	6	3.5	9.5	9	7.5	4.5
	265	4.5	4	3.5	2	8	7.5	6.5	4	11.5	10.5	9	5.5	14	13	11	6.5	2.5	2.5	2	1.5	4.5	4	3.5	2	6.5	6	5	3	8.5	8	6.5	4	10.5	9.5	8	4.5
	300	5	4.5	4	2.5	8.5	8	7	4	12.5	11.5	9.5	6	15.5	14	11.5	7	3	3	2.5	1.5	5	4.5	4	2.5	7	6.5	5.5	3	9	8	7	4	11	10	8.5	5
	330	5.5	5	4	2.5	9	9	7.5	4.5	13	12	10	6	16.5	15	12.5	7.5	3	3	2.5	1.5	5.5	5	4.5	2.5	7.5	7	6	3.5	9.5	9	7.5	4.5	11.5	11	9	5.5
Twin, bicycle	50	2	2	1.5	1	4	3.5	3	1.5	5	4.5	3.5	2.5	7	6	5	3	1.5	1	1	0.5	2	2	1.5	1	3	2.5	2	1.5	4	3.5	3	2	5	4	3.5	2
Spacing, 37 in.	75	2.5	2.5	2	1	4.5	4	3.5	2	6.5	5.5	4.5	3	8.5	7	6	3.5	1.5	1.5	1	0.5	2.5	2.5	2	1	3.5	3.5	3	1.5	5	4.5	3.5	2	6	5	4	2.5
Contact area, 267 sq in.	100	3	3	3	1.5	5.5	5	4	2.5	7.5	6.5	5.5	3.5	10	8.5	7	4.5	2	2	1.5	1	3	3	2.5	1.5	4.5	4	3.5	2	5.5	5	4.5	2.5	7	6	5	3
	125	3.5	3.5	3	1.5	6	5.5	4.5	3	8.5	7.5	6.5	4	11	9.5	8	5	2.5	2	1.5	1	3.5	3.5	2.5	1.5	5	4.5	3.5	2.5	6.5	6	5	3	8	7	5.5	3.5
	150	4	4	3	2	7	6	5	3	9.5	8	7	4	12	10.5	9	5.5	2.5	2.5	2	1	4	3.5	3	2	5.5	5	4	2.5	7	6.5	5.5	3.5	8.5	7.5	6.5	4
Twin tandem, tricycle	100	2.5	2	2		4.5	4	3.5		6.5	6	5.5		9	8	7		1	1	1		2.5	2	2		3.5	3	2.5		5	4.5	4		6	5.5	5	
Spacing, 31-63 in.	120	2.5	2.5	2		5	4.5	4		7.5	6.5	6		9.5	9	8		1.5	1.5	1		2.5	2.5	2		4	3.5	3		5.5	5	4.5		6.5	6	5.5	
Contact area, 267 sq in.	135	3	2.5	2.5		5.5	5	4.5		8	7	6.5		10.5	9.5	8.5		1.5	1.5	1.5		3	2.5	2.5		4.5	4	3.5		6	5	4.5		7	6.5	6	
	150	3	3	2.5		6	5	4.5		8.5	7.5	7		11	10	9		2	1.5	1.5		3	3	2.5		4.5	4	3.5		6.5	5.5	5		7.5	7	6.5	
	170	3.5	3	3		6.5	5.5	5		9	8.5	7.5		12	11	10		2	2	1.5		3.5	3	3		5	4.5	4		6.5	6	5.5		8	7.5	7	
Twin, tricycle	40	1.5	1.5	1.5		3	2.5	2.5		4.5	4	3.5		5.5	5	4.5		1	1	0.5		1.5	1.5	1.5		2.5	2	2		3	3	2.5		4	3.5	3	
Spacing, 37 in.	60	2	2	1.5		4	3.5	3		5.5	5	4.5		7	6.5	6		1.5	1	1		2	2	1.5		3	2.5	2.5		4	3.5	3.5		5	4.5	4	
Contact area, 267 sq in.	80	2.5	2.5	2		4.5	4	3.5		6.5	5.5	5		8	7.5	7		1.5	1.5	1.5		2.5	2.5	2		3.5	3	3		5	4.5	4		6	5	4.5	
	100	3	2.5	2.5		5	4.5	4		7	6.5	5.5		9.5	8.5	8		2	1.5	1.5		3	2.5	2.5		4	3.5	3.5		5.5	5	4.5		6.5	6	5.5	
	120	3.5	3	2.5		5.5	5	4.5		8	7	6.5		10.5	9.5	8.5		2	2	1.5		3.5	3	2.5		4.5	4	3.5		6	5.5	5		7.5	6.5	6	
Single wheel	10		1	1			1.5	1.5			2	2			2.5	2.5			0.5	0.5			1	1			1.5	1			1.5	1.5			2	2	
100-psi tire inflation	30		1.5	1.5			2.5	2.5			3.5	3.5			4.5	4			1	1			1.5	1.5			2	2			3	2.5			3.5	3	
pressure	50		2	2			3.5	3			4.5	4			6	5.5			1	1			2	2			2.5	2.5			3.5	3			4.5	4	
	70		2.5	2			4	3.5			5.5	5			7	6.5			1.5	1.5			2.5	2			3	3			4	4			5	4.5	

* Proof-rolling shall consist of 30 coverages of a heavy rubber-tired roller (150-psi, 30,000-lb minimum tire load) on each layer of base where the required CBR is in excess of 50 and on the top of the layer immediately under these layers.
** Hangar floors.

[after U. S. Army (25)]

required.

Compaction requirements for material under rigid pavements are given in TM 5-824-3 (93). These requirements are summarized below:

a. Base Course

1. Thickness less than 10 inches

   95 percent Modified AASHO

2. Thickness greater than 10 inches

   top 6 inches - 100 percent Modified AASHO

   below 6 inches - 95 percent Modified AASHO

b. Subgrade

1. Fill sections

   i. Cohesive - 90 percent Modified AASHO

   ii. Cohesionless

   top 6 inches - 100 percent Modified AASHO

   below 6 inches - 95 percent Modified AASHO

2. Cut sections

   i. Cohesive

   top 6 inches - 90 percent Modified AASHO

   ii. Cohesionless

   top 6 inches - 100 percent Modified AASHO

   18 inches below top 6 inches - 95 percent Modified AASHO

It is emphasized that the above specifications do not ensure adequate strength of the material, and that it will still be necessary to ascertain that the material has adequate strength to resist the applied load.

3. Blending

Blending makes possible the use of materials which by themselves will not meet existing specifications, but when blended in proper proportions will provide a suitable material.

Gradation and Atterberg limits for select materials and subbases are shown in Table 49 (25). If practical, suitable materials can be blended to meet these specifications; however, local materials are often available which will meet these criteria without requiring blending.

Gradation bands for combined materials to be used as base courses are shown in Table 50. Atterberg limit criteria should also be imposed to insure proper blending of base course components. These criteria are presented in Table 51 (95).

4. Special Considerations

In many instances, compaction and/or blending will provide a material of improved load carrying capacity. However, as mentioned earlier, this strength increase may not be permanent, and in some soils a high degree of densification may be injurious. These special considerations are discussed below.

a. Clays That Lose Strength When Remolded

The individual particles in certain clay soils have a definite structure. Destruction of this structural arrangement by the compaction process - even at a constant water content - will greatly reduce the strength of the material. The effect of remolding can be determined by strength tests on in situ and remolded specimens. If the undisturbed value is higher then no compaction should be attempted.

b. Silts That Become Quick When Remolded

Some deposits of silt, very fine sand and rock flour (ML and SM soils)

TABLE 49

GRADING AND ATTERBERG LIMITS FOR

SELECT AND SUBBASE MATERIAL

Material	Maximum Design CBR	Maximum Permissible Value				
		Size Inches	Gradation Requirements, percent passing		Atterberg Limits	
			No. 10	No. 200	LL	PI
Subbase	50	3	50	15	25	5
Subbase	40	3	80	15	25	5
Subbase	30	3	100	15	25	5
Select Material	20	3		25	35	12

[after U. S. Army (25)]

TABLE 50

DESIRABLE GRADATION FOR CRUSHED ROCK, GRAVEL, OR SLAG, AND UNCRUSHED SANDY AND GRAVEL AGGREGATES FOR BASE COURSES AND FOR MECHANICAL STABILIZATION

Sieve designation	Percent passing each sieve (square openings) by weight				
	Maximum aggregate size				
	3-inch	2-inch	1 1/2-inch	1-inch	1-inch sand-clay
3-inch	100				
2-inch	65-100	100			
1 1/2-inch	----------	70-100	100		
1-inch	45-75	55-85	75-100	100	100
3/4-inch	----------	50-80	60-90	70-100	
3/8-inch	30-60	30-60	45-75	50-80	
No. 4	25-50	20-50	30-60	35-65	
No. 10	20-40	15-40	20-50	20-50	65-90
No. 40	10-25	5-25	10-30	15-30	33-70
No. 200	3-10	0-10	5-15	5-15	8-25

[after U. S. Army (95)]

TABLE 51

ATTERBERG LIMIT REQUIREMENTS FOR BLENDING

Type of Construction	Atterberg Limit Requirements of Each Component	
	Plastic Index	Liquid Limit
Normal	5	25
Theater of Operation	10	36
Emergency	15	45

[after U. S. Army (95)]

when compacted in the presence of a high water table will pump water to the surface and become spongy with a significant loss of bearing value. In such cases, it is necessary to remove the source of water by lowering the ground water table. If this is not feasible, then the subgrade should not be disturbed and additional thicknesses of overlying better material must be used.

c. Clays With Expansive Characteristics

In many parts of the world, soils exist which swell when they absorb moisture and shrink when they dry. This may result in differential heaving of pavements that is intolerable. If the amount of swell is less than about 3 percent, special consideration will not normally be needed (95). A common way to treat such soils is to compact them at a moisture content and unit weight that will minimize expansion. A combination of moisture, density, CBR and swell which will give the greatest CBR and density consistent with a tolerable amount of swell must be selected. These will not necessarily be the optimum moisture content and unit weight determined by the modified AASHO compaction test.

d. Soils That Are Frost Susceptible

Many soils found in colder regions of the world undergo significant strength losses due to the action of frost. Pavements over these soils are frequently broken up as subgrades freeze in winter and thaw in spring. In particular, when the subgrades thaw in the spring they become extremely unstable, and in some cases it may become necessary to close a facility until the subgrade recovers its stability. The design of pavements in frost areas is a special procedure which is presented elsewhere (96). However, since frost susceptible soils do not exhibit the permanency of strength that often is responsible for the decision whether

to use chemical stabilizers, the engineer should be aware of which soils are frost susceptible and which are not. This information is given in TM 5-330 (96) and summarized below:

1. Non-frost susceptible soils

   Inorganic soils containing less than 3 percent by weight of grains finer than 0.02 mm.

   Uniformly graded sandy soils having less than 10 percent by weight of grains finer than 0.02 mm.

2. Frost susceptible soils

   These soils are listed in Table 52 in general order of increasing susceptibility. There is some overlapping of frost susceptibility within the groups.

TABLE 52

FROST SUSCEPTIBLE SOILS WITH RELATION TO PAVEMENTS

Group	Description
F-1	Gravelly soils containing between 3 and 20 percent finer by weight than 0.02 mm are the least affected of the frost susceptible soils.
F-2	Sands containing between 3 and 15 percent by weight finer than 0.02 mm.
F-3	(1) Gravelly soils containing more than 20 percent finer than 0.02 mm by weight. (2) Sands, except very fine silty sands, containing more than 15 percent finer than 0.02 mm by weight. (3) Clays with plasticity indexes of more than 12. (4) Varved clays existing with uniform subgrade conditions.
F-4	(1) All silts including sandy silts. (2) Very fine silty sands containing more than 15 percent finer than 0.02 mm by weight. (3) Clays with plasticity indexes of less than 12. (4) Varved clays existing with nonuniform subgrade conditions.

NOTE: Groups are listed in general order of increasing susceptibility.

[after U. S. Army (96)]

SECTION VIII

CONSTRUCTION FACTORS

1. Introduction

The engineer, having evaluated the soil, selected the type and amount of stabilizer, and considered the constraints imposed by site weather conditions, must survey the available construction equipment that might be used to implement the stabilization work. The objective of the efforts that transpire is to thoroughly mix the pulverized soil and the selected stabilizing agent in the correct proportions with sufficient moisture to permit proper and adequate compaction. A simple procedural approach that might be followed consists of:

a. Initial preparation

1. shape the area to proper crown and grade
2. scarify, pulverize and prewet the soil as required
3. reshape to crown and grade

b. Processing

1. spread the selected stabilizer
2. add water as required
3. mix
4. compact
5. finish
6. cure as required

Types of scarifying, mixing and compaction equipment include a

considerable range from that commonly used in agricultural operations to highly efficient specially designed soil stabilization trains. Mixing equipment may be grouped into traveling and stationary type roughly as follows:

a. Traveling mixers

   1. windrow type

   2. flat type

   3. multiple-pass rotary mixers

b. Stationary (or central) mixing plants

   1. batch type

   2. continuous flow type

Since the general objective of the operation and the principles involved are quite similar, the engineer must make a decision considering efficiency, expediency, and economy contingent upon the constraints generally imposed by the situation at hand.

Some discussions concerning the limitations and operational details of the various pieces of equipment used for mixing, placing and compacting stabilized soil seems warranted and is presented in the following paragraphs.

2. Traveling Mixers

Construction steps for various types of traveling mixing plants are discussed below:

a. Windrow type traveling plants

Since this type of stabilization equipment does not possess sufficient power to pulverize most soils, preliminary pulverization is usually necessary. The pulverized or prepared soil is then bladed into a windrow by a motor grader and formed by a screed to a uniform

cross section. The stabilizer is applied to the top of the prepared soil windrow with a suitable spreader. Mixing either occurs on the underlying layer or in a traveling pugmill. In the latter case the soil is picked up, fed to the pugmill and redeposited on the underlying layer. Initial dry mixing takes place as the first few paddles pass through the windrow. Water is then added through spray nozzles and the remaining paddles complete the mixing. The mixed soil is deposited in a windrow, spread by a grader and compacted.

b. Flat type traveling plants

Since most flat type mixing machines have a high speed pulverizing rotor, preliminary pulverization is usually not necessary. The only preparation required is shaping the soil to approximate crown and grade. The stabilizer is spread over the soil with a suitable spreader. The machine mixes the soil and stabilizer to a preselected depth on the underlying layer. The first rotors in the machine pulverize and dry-mix the soil and stabilizer. Water is measured through a meter and injected into the mixing chamber by a spray bar. The remaining rotors mix the soil, water and stabilizer.

c. Multiple pass rotary mixers

Since most rotary mixers were not designed to scarify, initial preparation includes loosening the soil with a scarifier, initial pulverization, and shaping to approximate grade and crown. The stabilizer is then spread on the ground and the first pass is made. The objective at this stage is to distribute stabilizer throughout the soil mass. Sufficient water is then added to bring the mixture to the desired moisture content (this step may vary according to the stabilizer used). The moisture is added in increments and each increment is mixed

with the soil and stabilizer. After the last increment of water is added, mixing is continued until the soil, stabilizer and water are thoroughly mixed through the entire depth and width of treatment. The material is then ready for compaction and finishing.

d. Other types of traveling plants

Various construction equipment manufacturers have combined several major pieces of equipment so as to eliminate one or more steps in the stabilization process. One example of this combination is the DUO-STABILIZER manufactured by the Seaman Corporation. This piece of equipment has the capability to scarify, pulverize, mix, level and compact soil and stabilized mixes.

e. Classification by shaft orientation

Traveling plants can be further classified by the orientation of the mixing shaft. Pugmill type plants have shafts that are parallel to the direction of travel. The windrow type traveling plant previously mentioned is an example of the parallel shaft machine. Due to the orientation of rotation, it is not feasible to attempt to pulverize or reduce in-place material with this type of machine. The parallel shaft machines should therefore be used only for mixing preconditioned or pulverized soil, water and stabilizer.

Traveling plants whose shafts lie across the direction of travel are classified as transverse rotary mixers. These mixers may have the capability of pulverizing in-place material depending on rotor characteristics such as speed, torque, depth of cut and production characteristics of the plant as a whole. With pulverization capability the plant has " one pass" potential. The flat type traveling plant and the multiple-pass rotary mixers mentioned above are example of transverse

mixers. The flat type is designed for single-pass operations while the rotary mixer is used for multiple-pass construction.

3. Related Stabilization Equipment

As soil stabilization outgrew its "step-child" status, methods such as manual distribution of dry admixtures gave way to specially designed spreader boxes and bulk distributors that meter and produce a uniform flow of agent. Spreaders are constructed along the same lines and possess similar characteristics as the aggregate spreaders presently used in bituminous surface treatment. The bulk spreaders or distributors range in capacity from 500 to 10,000 gallons. The Cyclone type bulk distributors are capable of spreading a metered, uniform flow of dry admix (lime, cement, salt, calcium chloride, etc.) on windrows of prepared soil or on in-place material. Some bulk distributors are equipped with pneumatic systems that pump the stabilizer directly into the mixing chamber of a transverse rotary mixer or traveling plant.

Emulsified asphalts and cutback asphalts are often spread by tank trucks equipped with spray bars, although injection through the rotary mixer spray bar system is more accurate and efficient. In the latter operation, the mixer's spray system is connected by a flexible hose line to a "nurse" truck which supplies the liquid. These distributors contain recirculation pumps or internal paddles to keep the additives in solution.

4. Stationary (or Central) Mixing Plants

Under some conditions, the off-site stabilization of soils is more suitable than on-site or road mixing. Some advantages of plant mixing over road mixing are:

a. On projects where submarginal soils have to be used, the soil must be processed to meet gradation requirements. It is a relatively simple matter for the contractor to install a bin, feeder and pugmill at the plant to add the stabilizing agent.

b. A more uniform mix of the stabilizer, soil and water is achieved.

c. No mixing is required on the road. This speeds up the on-site operations.

d. Moisture content may be more rigidly controlled.

e. Less loss of moisture occurs due to evaporation if travel time to the laydown site is kept to a minimum and the soil is covered en route.

f. Rollers may be used directly behind the laydown operation.

g. One inspector at the plant can control the gradation, moisture content, stabilizer content and mixing.

The combining of soil and stabilizer at a central plant is accomplished by the use of batch or continuous type plants or by expedient type plants set up at borrow pits.

The batch type plant operates on the same principles as the familiar concrete or hot mix asphalt plants currently in use. Preselected amounts of graded soil and stabilizer are combined with sufficient water to produce optimum properties in a given batch. Batches are produced at intervals of 30-90 seconds.

In the continuous type plant, addition of soil, stabilizer and water are regulated to produce a continuous flow of mixture in preselected proportions.

Several manufacturers produce a placer-spreader-trimmer that is of great benefit in central plant mixed stabilization. This equipment receives the mixed soil, places it on the roadway to the required depth, and trims the

surface to an initial grade. As an expedient laydown method, slightly modified asphalt pavers may be used to prepare the stabilized mixtures for compaction and finishing. Vibrating pads mounted on the rear of asphalt pavers have been used with some success for compaction.

5. Equipment Used for Expedient Soil Stabilization

a. On-site stabilization

Equipment such as disc harrows, scarifiers, plows, motor graders, and even large capacity scrapers have been utilized in the pulverization and mixing of soils and stabilizing agents. With advances in design of engineering equipment, these pieces of equipment have become outdated from the standpoint of mixture uniformity. Economics and timeliness in many instances, however, will require that some expedient method be used. In these situations equipment such as disc harrows, plows, etc. are extremely useful provided close control is maintained on mixture uniformity.

b. Off-site stabilization

Expedient off-site stabilization operations have been set up using on-site stabilization equipment in a borrow pit. Experience has shown that material produced in these operations is of doubtful quality due to nonuniform mixing and extreme difficulty of controlling moisture. This type of operation should be considered only as a last resort, regardless of economic or timeliness considerations.

6. Equipment Requirements of Limitations for Particular Types of Stabilization

a. Lime stabilization

1. Subgrade or subbase

A grader-scarifier and/or disc harrow can be used for initial scarification followed by a disc harrow or rotary mixer (flat type) for pulverization. Self unloading tankers for dry application and pressure liquid distributors are recommended for stabilizer application for efficiency and assurance of uniform application. The soil aggregate (or clod) size should be less than 2 inches before compaction. Ideally 100 percent of the soil clods should pass the 1-inch sieve and 60 percent should pass the No. 4 sieve.

Lime stabilization of heavy clays usually requires two mixing stages. Initial mixing and blending should be followed by a day or more of "mellowing." Final mixing can then take place resulting in a more uniform product.

i. Subgrade

Although disc harrows and grader-scarifiers are suitable for preliminary and initial mixing, high speed rotary mixers or single pass travel plants are essential for final mixing. Motor graders are generally unsuitable for mixing lime with heavy clays.

ii. Subbase

Both blade and rotary mixing have been used successfully. However, rotary mixers are preferred for more uniform mixing, finer pulverization and faster operation. The National Lime Association (86) offers methods for blade mixing. Rotary mixers should make 1-3 passes depending on type of equipment and soil.

2. Base stabilization

Equipment requirements and limitations for base stabilization resemble those for subbases. However, a rooter, tractor ripper, or preparator is usually necessary to reduce old asphalt surfacings to

suitable size particles. Since only one mixing stage is necessary, a multiple pass rotary mixer can be used provided the base material pulverizes readily. In other cases a single pass (pulverizing) mixer should be used to insure adequate pulverization.

3. Compaction

The most common practice for compaction is to compact in one lift, using a sheepsfoot roller until it walks out, followed by a multiple wheel pneumatic roller (10 ton); a steel wheel roller is then used for finishing. Single lift compaction can also be accomplished using vibrating impact rollers or heavy pneumatic rollers, with light pneumatic or steel wheel rollers being used for finishing. When light pneumatic rollers are used alone, compaction should be accomplished in thin lifts less than 2 inches thick. Slush rolling of base courses with steel wheel rollers should be avoided as a material of low shear strength is produced at the surface.

4. Central plant mixes

Central plant mixes should be placed by a placer-spreader-trimmer or asphalt concrete laydown machine to maintain uniformity. If these types of equipment are not available, aggregate spreaders, tailgate dumping and grader spreading can be utilized. However, spreading by use of a grader reduces the uniformity of the stabilized mixture and is not recommended.

b. Cement stabilization

1. Road construction

If the soil is friable a windrow type traveling plant can be used to mix the soil and cement. Thus, only scarification and blocking

into windrows is needed for preparation.

Flat type or single-pass mixers require no preliminary preparation unless the material is extremely hard, such as an old roadway. In these cases it would be beneficial to prewet and scarify.

With the multiple-pass mixer it is necessary to scarify the soil. Pulverization of the soil is also necessary when clays or hard, dense materials are encountered. These mixers are time consuming as several passes are needed to thoroughly process the soil.

If stationary plant-mixed material is used the mixture should be spread with spreader boxes. Dumping in piles and spreading with graders should be avoided as nonuniform densities often result.

Prior to compaction the soil-cement mixture should be pulverized until 100 percent of the soil clods pass the 1-inch sieve and 80 percent pass the No. 4 sieve.

2. Compaction

Plate vibrators, grid and segmental rollers have been satisfactorily used to compact mixes of cement and nonplastic granular soils. Sheepsfoot rollers should be used for all but the most granular soils with ballast increased to provide contact pressure in the following order: friable, silty and clay-sand soils, 75 to 125 psi; clay-sands, lean clays and silts that have low plasticity, 100-200 psi; medium to heavy clays and gravelly soils, 150-300 psi. Lift thickness for sheepsfoot rollers should not exceed 8 inches (loose).

Pneumatic tired equipment can be used to compact very sandy soils with little or no binder. A heavy roller is used to compact and a light roller is used to finish. Cohesionless sand may be compacted with large track type tractors with screed plates. Compaction is

obtained by the weight and vibration of the tractor. Twelve-ton, three-wheeled steel rollers are commonly used in some areas to compact granular soils. Soils containing little or no binder material and that have low plasticity are best suited for this method. Maximum lifts should not exceed 6 inches.

c. Asphalt stabilization

Since stabilization with bituminous materials requires a well mixed and uniform product, central plant mixing is preferred. If in-place mixing is required, a traveling plant mixer should be used. Those pieces of equipment which pick the soil up from the subgrade and mix in a pugmill are preferred. Grader mixing of soil and liquid should not be used due to poor mixing and the resulting nonuniform product.

The asphalt should be distributed to the soil mass through the spray bar system in the mixing chamber. Use of truck distribution of asphaltic materials causes puddles in the wheel tracks and a resulting nonuniform mixture.

Compaction with a combination of pneumatic tired and steel wheel rollers yields the highest density.

7. <u>Summary of Construction Requirements and Limitations</u>

a. Lime stabilization

Pulverization and mixing should continue until the lime is uniformly mixed and the soil clod size is such that 100 percent passes a 1-inch sieve and 60 percent passes the No. 4 sieve (exclusive of any gravel and stone).

b. Cement stabilization

Pulverization and mixing should continue until the cement is uniformly mixed and the soil clod size is such that 100 percent passes a 1-inch sieve and 80 percent passes the No. 4 sieve (exclusive of any gravel or stone).

c. Bituminous stabilization

Central batch plants, together with other specialized equipment, are necessary to produce a uniform, high quality bituminous stabilized soil.

As discussed in this section, various types of scarifying, pulverizing, mixing, spreading and compacting equipment can be used for a particular stabilization job. The type of equipment selected by the engineer is often determined by availability. Thus, specific types of equipment have not been recommended, but instead general guidelines suggested.

Information contained in this chapter has been used in forming Tables 14, 15 and 16 presented previously.

SECTION IX

ENVIRONMENTAL FACTORS

1. Introduction

Stabilization - particularly with chemicals - may be ineffective unless the weather and rainfall conditions are satisfactory. It is the intent of this section to discuss the situations which may be detrimental to stabilized soils and to describe general methods which can warn the engineer of these conditions. Some of these are expressed in terms of constraints or precautions which will prohibit the application and use of certain stabilizers. It is realized that military engineers faced with hasty forward construction may not always be able to honor these constraints and will have to accept a substandard job. However, they can still be of value in planning a program, and in aiding in the selection of a particular stabilizer when more than one type will suffice.

2. Sources and Types of Available Environmental Information

A review of literature reveals that little information has been developed to quantitatively define environmental factors. Weinert (97) has reported on a climatic index which was developed to indicate where moist environments might be harmful to certain unstabilized aggregates. The Corps of Engineers use a freezing index (96) to determine depths to which frost might penetrate pavements. Both of these - and similar concepts developed by others - are helpful in pavement design, but appear to be of limited value in defining environmental factors which must be considered with stabilized soils, particularly during the construction period.

Until appropriate factors are quantified, the engineer must be satisfied with a more qualitative approach which uses general environmental information in conjunction with certain information presented later in this section. Considerable engineering judgment must be exercised, but an awareness of the possible problems may prevent unsatisfactory jobs.

In general, sufficient environmental information should be obtained to develop a general climatic profile of the area in which construction is being planned. Most of the necessary information can be obtained from Air Force meteorologists. Otherwise, local weather records, records available from ESSA (Environmental Science Services Administration) and other such sources, can be used.

The following information can be helpful:

a. Temperature

1. Average maximum and minimum monthly temperatures

2. Date of last freeze in spring and first freeze in fall (earliest dates, latest dates and average dates are helpful)

3. Freezing Index (number of degree days of temperature below 32°F)

4. Ground temperature versus air temperature relationships

b. Rainfall

1. Average annual rainfall

2. Average monthly rainfall

3. Average minimum and maximum monthly rainfall

3. Influence of Temperature and Rainfall on Soil Stabilization

a. Temperature

Two primary factors must be considered with respect to temperature influence on chemically stabilized soils. First, the temperature must

be sufficiently high to permit mixing of stabilizer and soil, and for necessary chemical reactions to occur. Second, stabilized materials which require curing must have adequate curing time to resist the effects of subsequent freezing temperatures or freeze-thaw cycles. In both respects, requirements for bituminous materials differ from cement and lime.

Bituminous stabilization requires high enough temperatures to obtain thorough mixing, and to subsequently evaporate the volatiles (either hydrocarbons or water), as well as temperatures which permit adequate compaction. Lime-and cement-stabilized soils are dependent on chemical reactions for strength gains. At temperatures near or below freezing these reactions virtually halt, but as the temperatures rise, the speed of reaction roughly doubles for every 10°C increase in temperature. Thus, lime-and cement-stabilization must take place under favcrable temperatures to obtain effective strength increases; however, temperature effects on lime are more critical than for cement. Soils can be modified with lime and cement with little regard for temperature unless it is well below freezing and expected to remain that way for a lengthy period of time.

General requirements for stabilized soils with respect to temperature are discussed in greater detail below:

1. Bituminous stabilization

i. Asphalt cement

In most cases where asphalt cement is used, it will be hot-mixed in central plant, transported to location and placed. Various temperature specifications exist for this material (13), but all generally require that material shall not be placed unless the air temperature is at least 40°F and rising, and that placement be discontinued when the air temperature reaches 40°F and

is falling. In addition, the material should not be placed on a frozen underlying layer. The above applies particularly for thin layers; for thick lifts the temperature is usually not as important since the heat is held in the material for longer periods of time.

ii. Cutback asphalts

The Asphalt Institute (16) has suggested temperatures (Table 53 and Figure 29) to ensure that the asphalts will not be too viscous to spray and mix with the aggregate. It is also suggested that the aggregate temperatures be not less than 50°F. In expedient construction, it is felt that this requirement can be relaxed to a minimum aggregate temperature of 40°F if correct spraying temperatures can be maintained. Since these asphaltic materials contain hydrocarbon volatiles, low temperatures will somewhat decrease the speed of evaporation. Mixing time may need to be increased as temperatures decrease.

iii. Asphalt emulsions

Temperature ranges for mixing and spraying of emulsions are also given in Table 53. It is felt that the low temperature restrictions can again be relaxed to 40°F, and in extreme emergencies, somewhat lower mixing temperatures can be tolerated. However, since the volatile component is water, temperatures at or below freezing will not allow volatiles to escape. In addition, freezing temperatures can be harmful to emulsions even before they are applied to soils.

2. Lime-and cement-stabilization

As mentioned previously, these materials rely on chemical reac-

TABLE 53

MIXING AND SPRAYING TEMPERATURES FOR

VARIOUS GRADES OF LIQUID ASPHALT

Type and Grade	Suggested Temperature	
	For Mixing*	For Spraying
RC, MC, and SC Grades		
30	60-105°F	See Figure 29
70	95-140°F	
250	135-175°F	
800	165-205°F	
3000	200-240°F	
Anionic		
RS-1	**	75-130°F
RS-2	**	110-160°F
MS-2	50-140°F	100-160°F
SS-1	50-140°F	75-130°F
SS-1h	50-140°F	75-130°F
Cationic		
RS-2K	**	75-130°F
RS-3K	**	110-160°F
CM-K	50-140°F	100-160°F
SM-K	50-140°F	100-160°F
SS-K	50-140°F	75-130°F
SS-Kh	50-140°F	75-130°F

*Because the aggregate temperature controls the mix temperature, aggregate temperatures below 50°F or above the temperature of the liquid asphalt should not be permitted.
**Seldom used for mixing.

[after Asphalt Institute (16)]

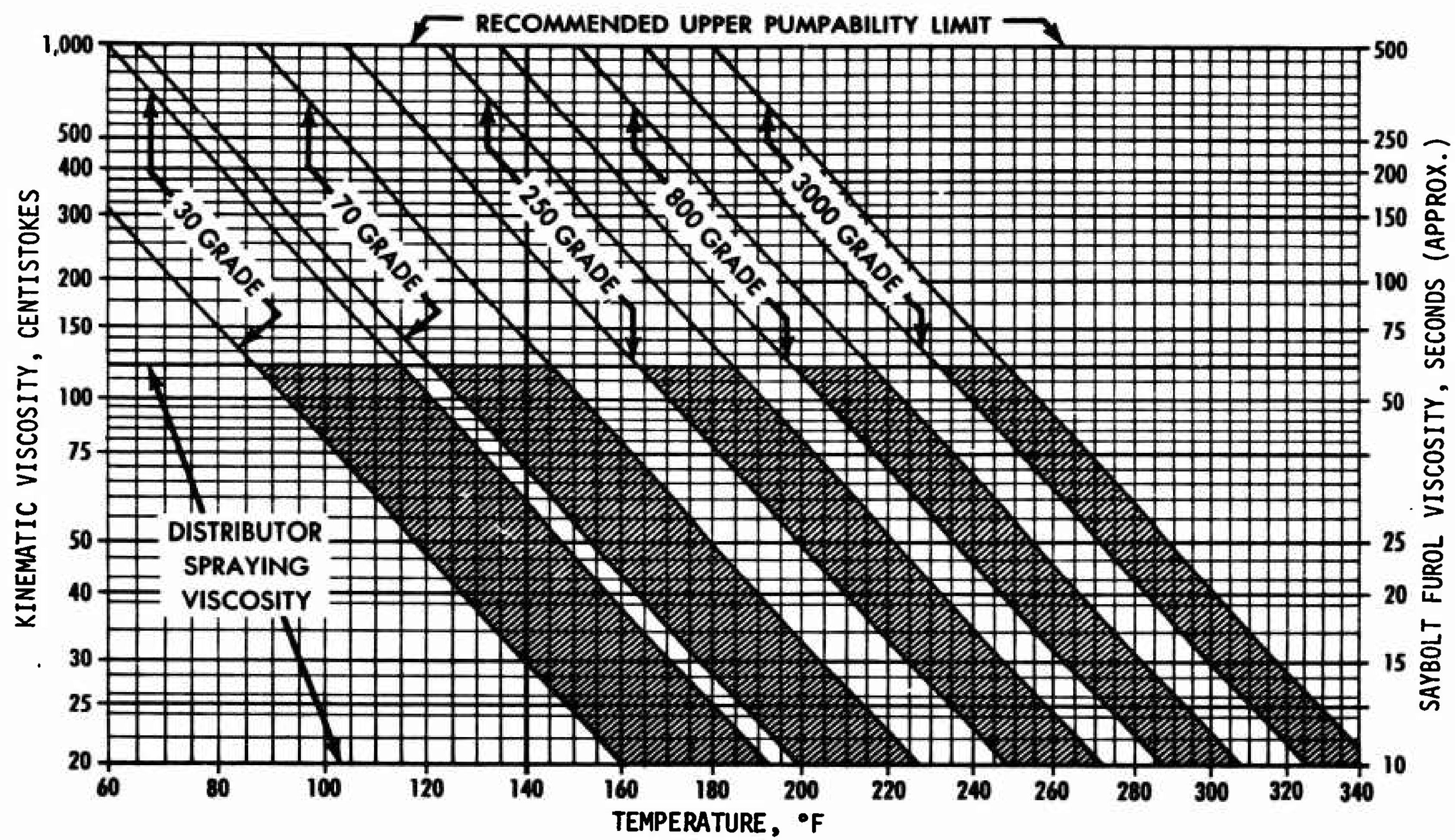


FIGURE 29. TEMPERATURE-VISCOSITY OF LIQUID ASPHALTS

[after the Asphalt Institute (16)]

tions for strength increases. In general, cement-stabilized soils can be expected to gain strength at a more rapid rate than lime-stabilized soils. The Portland Cement Association recommends that soil-cement not be placed when the temperature is 40°F or below. It is also important that the stabilized material not be subjected to freezing conditions during the period of strength gain, as this may disrupt the material due to frost action. For this reason, soil-cement should not be subjected to freezing temperatures for a period of 7 days after placement. If short, infrequent freezes are anticipated, an insulating covering of hay, straw, etc. may be used during the curing period.

Lime-stabilized soils require about 4 weeks of 60-70°F temperature to allow hydration (86). The stabilized soils should not be subjected to freezing temperatures during the hydration period. Lower temperatures, as long as they are above freezing will only retard strength gain.

There are no well-documented requirements for modified soils. However, the necessary chemical reactions (cation exchange, etc.) will take place fairly rapidly as long as the temperatures do not drop below freezing. If freezing does occur, the chemical processes should reactivate as the temperatures increase, and modification will be delayed. In general, whenever temperature conditions for stabilization cannot be met, modification can still be expected. But it is necessary that adequate mixing of stabilizer and soil be accomplished before low temperatures set in.

b. Rainfall

Wet weather will not always terminate a stabilization project. If the

stabilization operation is properly planned, then only certain portions will be halted by rainfall. This is discussed below.

1. Bituminous stabilization

Mixing of bitumen on the roadway cannot be accomplished effectively during periods of rainfall. Heavy rains on mixed but uncompacted stabilized material may result in nonuniform bitumen coating. Central plant mixing can take place during rainfall, but placing and compaction of the hot-mixed asphalt concrete should not be attempted until the rain ceases. Rainfall after compaction can be detrimental if cutback or emulsified asphalts are used as it may prevent adequate evaporation of the volatiles. Extended periods of rainfall after compaction may prevent the remaining volatiles from evaporating and result in an unstable layer.

2. Lime stabilization

Lime should not be spread during periods of rainfall as uniform distribution in the soil mass will not be possible during mixing. Rainfall during mixing and compaction can be tolerated provided the moisture content build-up in the soil does not exceed that required for compaction. Light rains curing the curing period can be helpful; however, heavy rainfall may cause erosion of the stabilized layer.

3. Cement stabilization

Cement should not be spread during periods of rainfall as uniform distribution in the soil mass will not be possible during mixing. If rains do occur during spreading every attempt should be made to mix the cement into the soil before the cement starts hydrating. Rainfall during mixing and compaction can be tolerated

provided the moisture content does not exceed that required for compaction. Light rains during the curing period can be helpful; however, heavy rainfall during early periods of the curing can create erosion of the stabilized layer.

4. Summary of Environmental Requirements and Limitations

Yearly temperature and rainfall data are available for most parts of the world and should be collected during construction planning stages. If at all possible, stabilization should be scheduled during periods of high temperature and low rainfall.

Specifically, the engineer should make every attempt to schedule construction such that:

a. spreading of the stabilizer, mixing and compaction occurs during periods of warm, dry weather

b. curing occurs during warm and relatively dry weather in order that sufficient strength is achieved prior to traffic or prior to freeze-thaw cycles

Information contained in this section was used in developing Tables 14, 15 and 16 presented previously.

SECTION X

RECOMMENDATIONS FOR FUTURE RESEARCH

1. Introduction

Should the need arise, the Air Force must be in a position to provide facilities to support aircraft operations throughout the world. Thus pavements, as well as other support facilities, must be provided for both aircraft and supply operations. The construction of these pavements often requires the use of stabilized materials for either the subgrade or base course. With this in mind, the Air Force has embarked on a program of research to provide engineers with the necessary knowledge to effectively utilize stabilized materials as an integral part of the pavement.

A research project undertaken by Texas A&M University has resulted in the soil stabilization index system described in this report. The index system presents information for the engineer so that he can systematically determine:

a. the type of stabilization that can be used with a particular soil

b. the quantity of stabilizer to be used

c. a strength indication, which may or may not be compatible with a pavement design system

However, this system assumes that stabilization is necessary, and furthermore it assumes that the layer in the pavement structure that will be stabilized has been ascertained. To properly determine the need for stabilization and the location of the stabilized layer in the pavement structure, pavement design methods must be utilized.

Criteria that were used to develop the soil stabilization index system were based on the experience and research of many individuals and groups. Unfortunately the majority of stabilized materials have been used in highway systems rather than airfield pavements, and furthermore the majority of reported stabilization research has been on North American soils. Thus, the criteria are based on only a limited number of soils when one considers the worldwide application of the system by the Air Force, and on pavement systems which are loaded with vehicles of lower gross loads, lower tire pressures and simpler wheel configurations than might be needed by the Air Force.

It is important that these and other limitations of the developed soil stabilization index system be recognized and that the Air Force carefully plan future research in areas of soil stabilization where gaps in knowledge exist. In this manner, unnecessary duplication will not exist. It is the intent of the authors to indicate the gaps in knowledge as revealed by the development of the index system, and furthermore to suggest future research needs that should be undertaken by the Air Force so stabilized materials can be effectively used as an integral part of the pavement. Below, several general areas of recommended research are discussed followed by research requirements and tests needed to complete Phase II of the research on the index system.

2. General Areas of Recommended Research

In some instances the research discussed below overlaps and extends the scope of research needed to validate the index system.

a. A systems approach is needed to determine and to illustrate the inter-relationship of pavement design and soil stabilization.

The systems approach views the entire system of components as an

entity rather than simply as an assembly of individual parts. Each component or variable in the system is designed to fit properly with the other components of the system rather than functioning by itself. The system can be divided into subsystems for the purpose of defining research needs, thus allowing both the sponsor and the research agency to more clearly define the mission of the particular research project in light of the overall research needs of a broad general program such as pavement design. The systems approach (98, 99, 100, 101, 102, 103) also inserts compatibility, interaction and feedback between pavement design methods, material characterization and field performance.

More specifically, the systems approach points out the need for material characterization to provide a basis for analyses to preclude failure of the pavement structure due to rupture, distortion and disintegration. In addition, the interaction of traffic, construction variables and environmental conditions must be considered when characterizing stabilized materials for both short- and long-term use. The importance of field evaluation and feedback to the design method can not be overemphasized and considerable effort should be expended on collecting data on existing and planned facilities.

An example of a simplified systems approach with emphasis on stabilized materials is illustrated in Figure 30.

b. A pavement design method should be developed which will adequately recognize the benefits of utilizing stabilized materials in various layers of the pavement.

A pavement design method should be capable of identifying the optimum location and thickness of stabilized layers in the pavement for specific aircraft and for a range of subgrade strengths. It

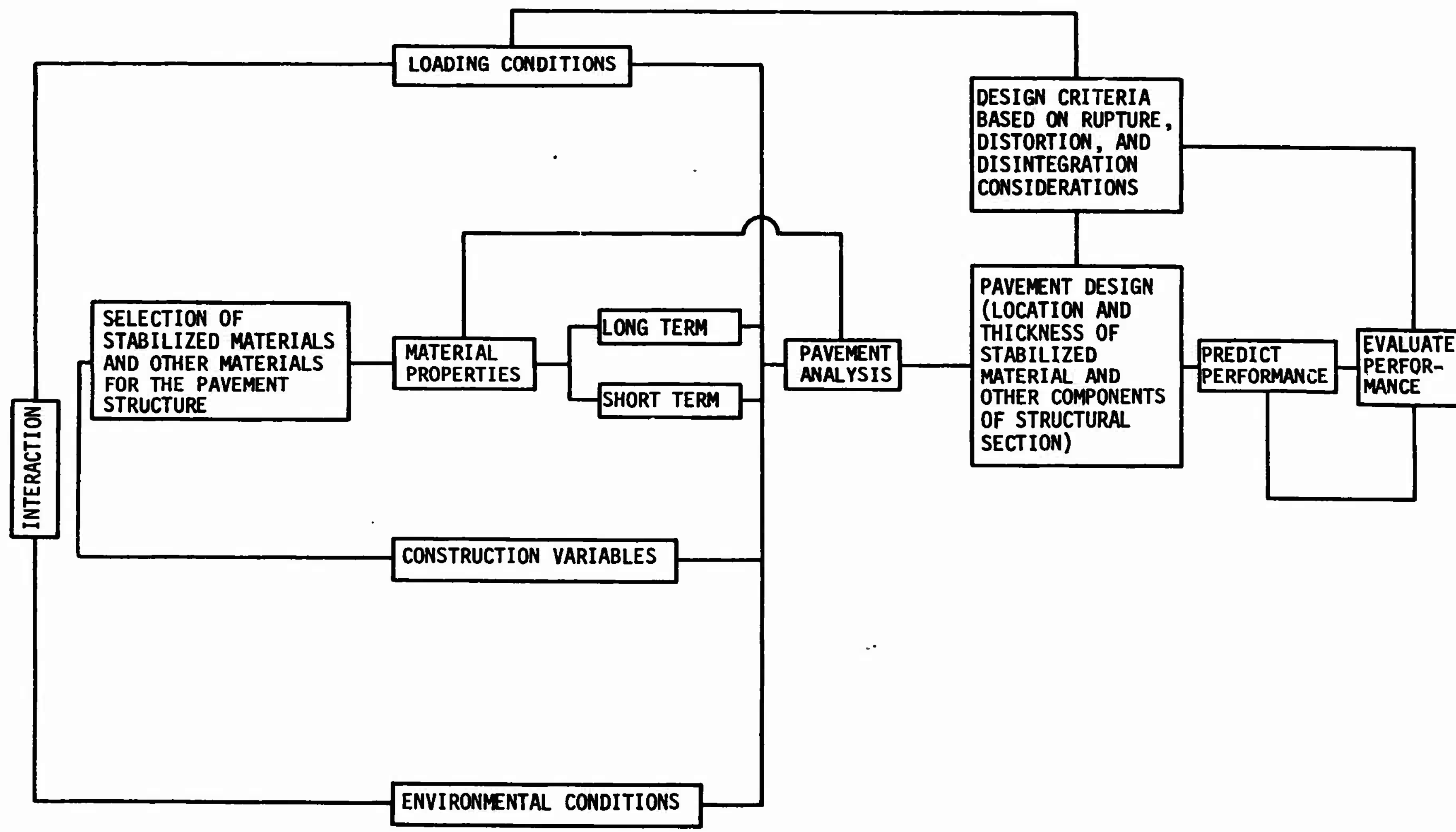


FIGURE 30. A SIMPLIFIED PAVEMENT DESIGN SYSTEM WITH EMPHASIS ON STABILIZED MATERIALS.

should fully utilize the strength available from the stabilized material. This is not always the case with the present CBR design procedure. For example, cement-stabilized materials are now restricted to a maximum design CBR of 50. This value was reportedly based on performance of test sections constructed during World War II. Its purpose was to reduce reflected shrinkage cracks and to insure an adequate thickness of overlying material to prevent the wearing surface from slipping at the interface with the stabilized base. With the present tendency towards thicker cross sections, this requirement may be completely outdated, or at least invalid for the majority of stabilization projects.

A rational test method should be included which will adequately consider the benefits of stabilized materials. This test method should result in parameters which are compatible with the pavement design method. Such a pavement design system and method for determining material properties has been proposed by Monismith (102).

c. The soil stabilization index system as a whole should be validated with soils and airfield construction experience from throughout the world.

This should be a continuing operation and criteria that are shown to be invalid should be corrected. Undoubtedly, much of the information that is needed will become available from other than U. S. military sources. However, the Air Force itself can collect much of this information as discussed in the recommendation below.

d. The Air Force should institute a debriefing system for its officers who have received field experience in soil stabilization.

The personnel rotation system used by the Armed Forces does not lend itself to continuity of knowledge from previous construction projects. In Viet Nam, for example, excellent knowledge is available from officers

who have conducted soil stabilization projects in that country. But when these personnel are reassigned they take this information with them leaving techniques and methods to be rediscovered by the next man on the job. *It cannot be emphasized too strongly that the Air Force should take steps to prevent this excellent first-hand information from being lost.* By means of a controlled debriefing session, the Air Force could obtain, sort and disseminate this information. This would not only provide solutions to many existing problems, it would also help to identify problem areas that must be researched.

The "key word in context" method (104) would provide a systematic means of retrieving and storing this information. Key words, which relate to all important aspects of any particular stabilization method, serve to "jog" one's memory, and this information - including numerical data - can be stored and arranged for recall with a digital computer.

e. Air Force requirements for expedient and nonexpedient construction should be carefully detailed.

These requirements are extremely important as they will influence both the stabilization index system and any subsequent pavement design system which might be developed.

f. Detailed durability requirements and appropriate durability tests for lime, cement and asphalt stabilized materials are sorely needed.

Present durability requirements have been developed primarily for highway pavements, and it is not known whether these are applicable to airfield pavements. Thus, detailed durability requirements should be defined for airfield construction, and durability tests should be adopted or developed to insure that these requirements are met.

From the testing viewpoint, only the freeze-thaw test used for cement stabilized soils is a well-accepted durability test, and it is not apparent that this is an appropriate durability test to use on a worldwide basis. Attempts to correlate unconfined compression tests with durability (such as has been done by the Portland Cement Association and the University of Illinois) are notable improvements in durability testing, at least from the standpoint of simplifying and decreasing the amount of time for durability tests. More detailed investigation of the validity of these tests appears to be warranted.

It should be emphasized that because of the varying requirements of the Air Force, which range from mobility to long-term airfields, durability specifications for stabilized materials under varying situations becomes a significant problem.

g. <u>Field methods of mixing stabilizers into soils should be investigated</u>.

The problems in this area are considered to be:

1. determining those soil and stabilizer properties that influence mixing
2. determining the degree of mixing that is required
3. determining the best type of mixing equipment

The Air Force Weapons Laboratory is presently reviewing this problem, and several comments in this respect are discussed below.

First, the problem of mixing is a very practical one, and one should be wary of highly theoretical approaches to the problem. Detailed investigations of physico-chemical properties of soils that influence mixing can be performed without ever solving the real problem of how to distribute the stabilizer into the soil.

Second, it is believed that more than soil properties alone influence mixing. Rather, it is the compatibility of soil and stabilizer that must be investigated. Thus, if one is looking at physico-chemical properties of soils without looking at the influence of the stabilizer on these properties, the result is liable to be misleading.

Third, the basic need seems to be a fresh approach to the mixing equipment, which has, for the most part, remained unchanged in concept since World War II. In cohesive soils, for example, the processes of plowing, discing and tilling are holdovers from farming operations. At best, their efficiency is low. Alternate approaches to destroying the natural cohesion of the clods of soil are by adding sufficient liquid, by vibration, by forcing the clods between narrowly spaced rollers, etc. Once these clods are broken down, the stabilizer can be easily added to the soil. Another example is a new method of producing hot-mix asphalt stabilized materials which is presently used in the state of Washington whereby the asphaltic cement is sprayed directly into the rotating dryer instead of being mixed in a separate pugmill. This method can be used in relatively poor environmental conditions, the equipment is portable, it can be used for expedient as well as nonexpedient operations, and it will provide a stabilized material with immediate strength and durability.

Finally, it is necessary to determine what soil properties need to be improved as this may dictate the amount of mixing necessary. If strength improvement is the sole criterion, it may be done at the expense of durability. The Air Force requirements vary and durability is not particularly a problem in short term mobility operations whereas shear strength is. In nonexpedient operations, durability may be more

important than short term strength gains.

h. The feasibility of calcining soils rather than stabilizing in the conventional manner should be investigated.

Many soils can be effectively converted to synthetic aggregates by kiln-firing. Instead of using temperatures high enough to produce "bloating" (resulting in lightweight aggregates), the Texas Highway Department has used lower temperatures to produce a durable but non-expanded aggregate. In several instances this material has been mixed with a local field sand to produce a satisfactory base course. It has also been used in asphaltic concrete and surface treatments. Although lightweight aggregates have been used for over 30 years and have a proven performance record, aggregates produced with lower temperatures have been used less than 10 years and thus have a shorter experience record. It is believed that the economics and logistics of such an operation should be investigated initially, followed by detailed durability and strength testing of aggregates produced from a variety of soil types.

i. A long range program to develop new chemical additives should be instigated.

Although past research on the development of additives other than lime, cement and bitumens has not been too encouraging, it is felt that research in this area should not be terminated. Rapid advances in the chemical field have produced new compounds daily and eventually this must result in improved stabilizers which are also economically feasible. Desirable characteristics of such stabilizers are:

1. produce high failure strains under slow rates of loading
2. produce high elastic moduli at fast rates of loading

3. adhere to soils coated with water or make use of the water that coats soil grains to produce an increase in strength

j. Environmental and construction factors in the index system should be quantified.

Climate and construction factors now enter the index system primarily as precautions, that is, they serve to warn the engineer that he must have certain climatic conditions and equipment to perform a particular stabilization effort. To be of greatest aid to the engineer, environmental and construction factors should be quantified. If this can be accomplished, this aspect of the index system will be greatly simplified. There is no doubt that these two important factors can be improved upon during the course of Phase II research on the index system, but it is also obvious that the development of a mathematical model cannot be accomplished within the scope of the present research.

3. Specific Research Recommendations Related to Validation of the Index System

Review of criteria and development of the soil stabilization index system has revealed certain specific areas of research that should be undertaken. In each instance, some degree of research will be accomplished during the validation of the index system. However, such a significant amount of information is required, and the scope is so broad, that it is believed that additional long range research will be necessary to complete the validation. Specific tests and criteria that need to be evaluated follow:

a. Marshall stability test criteria for asphalt stabilized soils should be reevaluated.

The criteria used in the index system for asphalt treated materials were based on the Marshall test method. These criteria are probably

overly conservative for asphalt cement treated base, but they may not be conservative for emulsion-and cutback-stabilized materials used for airfield pavements. The selected criteria need to be carefully reviewed, and new tests should be specified if the Marshall test proves to be unsatisfactory.

b. Verification of the pH test used for estimating lime contents should be undertaken on soils of world-wide distribution.

This test, because of its simplicity, offers considerable promise in rapidly estimating lime contents and in determining the reactivity of lime with soils. The University of Illinois, and others, have information on this test method, but it is presently limited to only a small number of soil types. Even though additional information will become available during verification of the index system, this will still encompass only a small number of the many worldwide soil types. Thus, even if the test proves to be satisfactory for the soils investigated, continual verification will still be needed.

c. The criteria used for the cement stabilization subsystems should be closely reviewed.

The cement stabilization subsystems are based on criteria largely obtained from the Portland Cement Association. A wider distribution of soils should be investigated using the Portland Cement Association tests. Also, the pH and sulfate tests should be validated on a wider range of soils.

4. Proposed Program for Phase II Research

Phase II research associated with the development of the soil stabilization index system will be aimed at the following specific objectives:

a. Laboratory verification of the index system will be undertaken.

Soils with the properties listed below will be tested to determine initial physical properties and will then be stabilized with the appropriate stabilizers according to the index system. The selection of soil properties was governed by the need to test each major group in the index system with particular emphasis on a few groups where the present criteria are most questionable. An attempt will be made to locate as many as possible of these soils from existing or proposed Air Force facilities so that field performance information can be obtained.

Sample No.	Percent Passing No. 200 Sieve	Plasticity Index	Sulfate Content	Organic Content
1	>25	>30	high	low
2	>25	>30	low	low
3	>25	>30	high	high
4	>25	>30	low	high
5	>25	>10<30	high	low
6	>25	>10<30	low	low
7	>25	>10<30	high	high
8	>25	>10<30	low	high
9	<25	<6	low	high
10	<25	<6	low	low
11	<25	Non-plastic	low	low
12	<25	>10	low	low
13	<25	<10	low	low
14	>25	<10	low	low

The following standard tests will be pefomed on each soil:

1. grain size analysis

2. Atterberg limits

3. moisture-density relations

4. pH

5. sulfate content

6. organic content

Each soil will then be stabilized with the most appropriate stabilizer(s). In most cases two and perhaps three stabilizing agents will be used. For each stabilizing agent, the following tests are anticipated:

1. Lime

   At least three lime contents will be selected to bracket the optimum lime content. At each lime content, moisture-density and pH tests will be performed. Unconfined compression tests will be performed on freeze-thaw specimens (at three different cycles of freezing and thawing), on soaked specimens and on unsoaked specimens, all molded at the optimum moisture content for each lime content.

2. Cement

   At least three cement contents will be selected to bracket the optimum cement content. At each cement content, moisture-density tests will be performed. Specimens will be molded at the optimum moisture content for each cement content and will be subjected to appropriate wet-dry and freeze-thaw cycles. Unconfined compression tests will be performed on specimens, and the validity of the rapid tests for determining cement content will be ascertained.

3. Asphalt

   It is anticipated that roughly four of the selected soils will be suitable for stabilizing with asphalt cement. The remainder will be stabilized with cutbacks and emulsions. A "fluids"-density curve

will be obtained on each stabilizer-soil combination. Marshall stability tests will be performed on specimens at two different temperatures (140° and 77°F) and Moisture Vapor Susceptibility tests will also be conducted.

b. <u>Selected soils used to verify the index system will be subjected to repetitive load testing</u>.

The purpose of this testing is to determine the elastic modulus and fatigue behavior of stabilized soils. Exploratory testing on a limited number of soil types will be performed to develop the most acceptable test procedure and equipment. The procedures initially used will be:

1. Unsupported beam
2. Unsupported diaphragm
3. Supported diaphragm

The most suitable of these procedures will then be used to test other stabilized soils. Based on information obtained from these tests, an attempt will be made to predict certain elastic parameters from the more standard tests performed on stabilized materials. Not only will the repeated load tests provide validation for the index system, it is hoped that this information will form the genesis for combining a pavement design system with the soil stabilization index system.

c. <u>The index system in its present form will be presented and discussed with various authorities in soil stabilization</u>.

The index system presented in this report resulted from considerable literature survey and discussion with many individuals who have not seen the final result of the system. Before the system is subjected to a significant amount of laboratory verification, it is believed that these individuals - many of whom represent producer organizations - should be

given the opportunity to critique the system and make their suggestions regarding possible areas of revision. This will be done only with prior Air Force approval.

APPENDIX A

EXPEDIENT SUBGRADE STABILIZATION SYSTEM

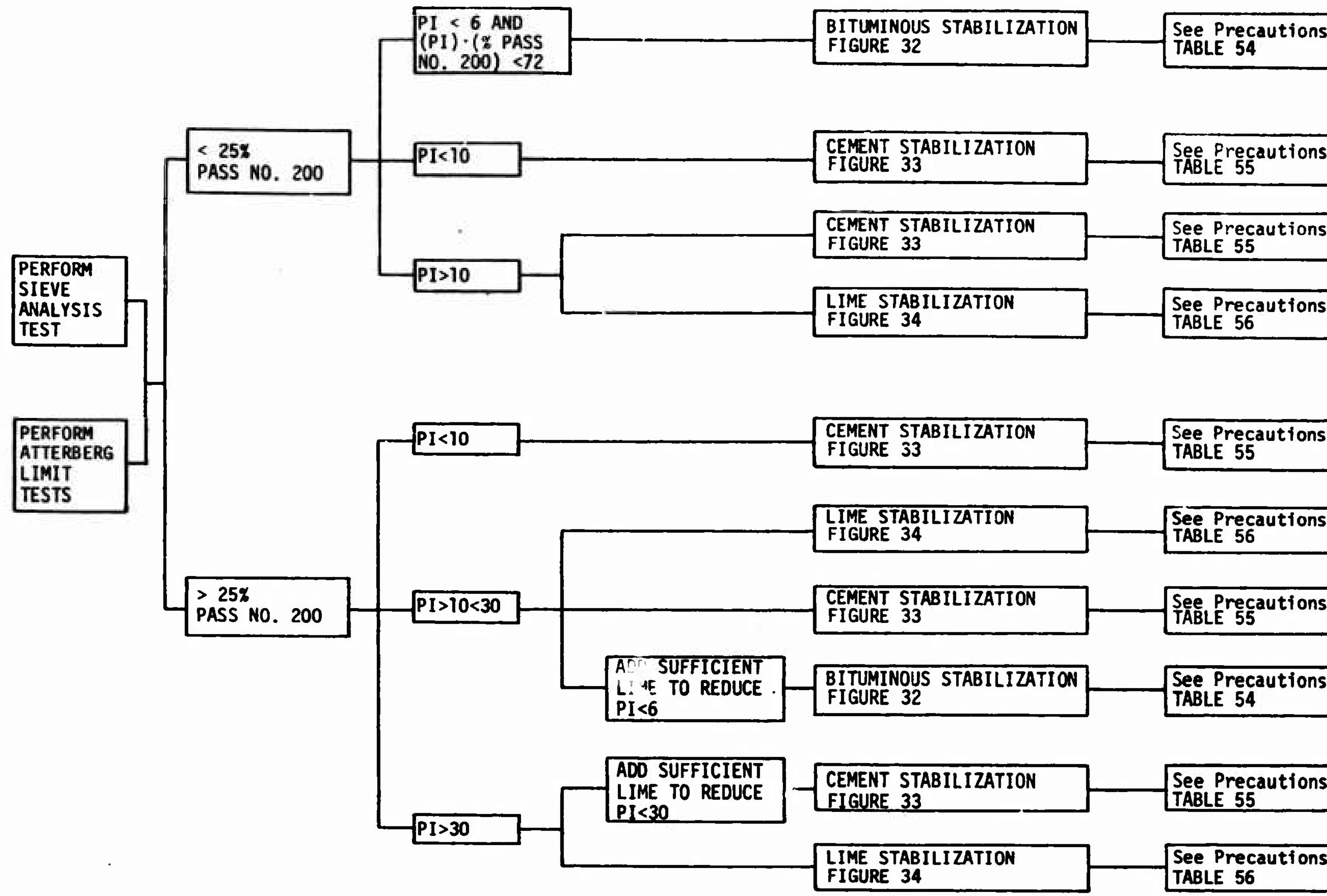


FIGURE 31. SELECTION OF STABILIZER FOR EXPEDIENT SUBGRADE CONSTRUCTION

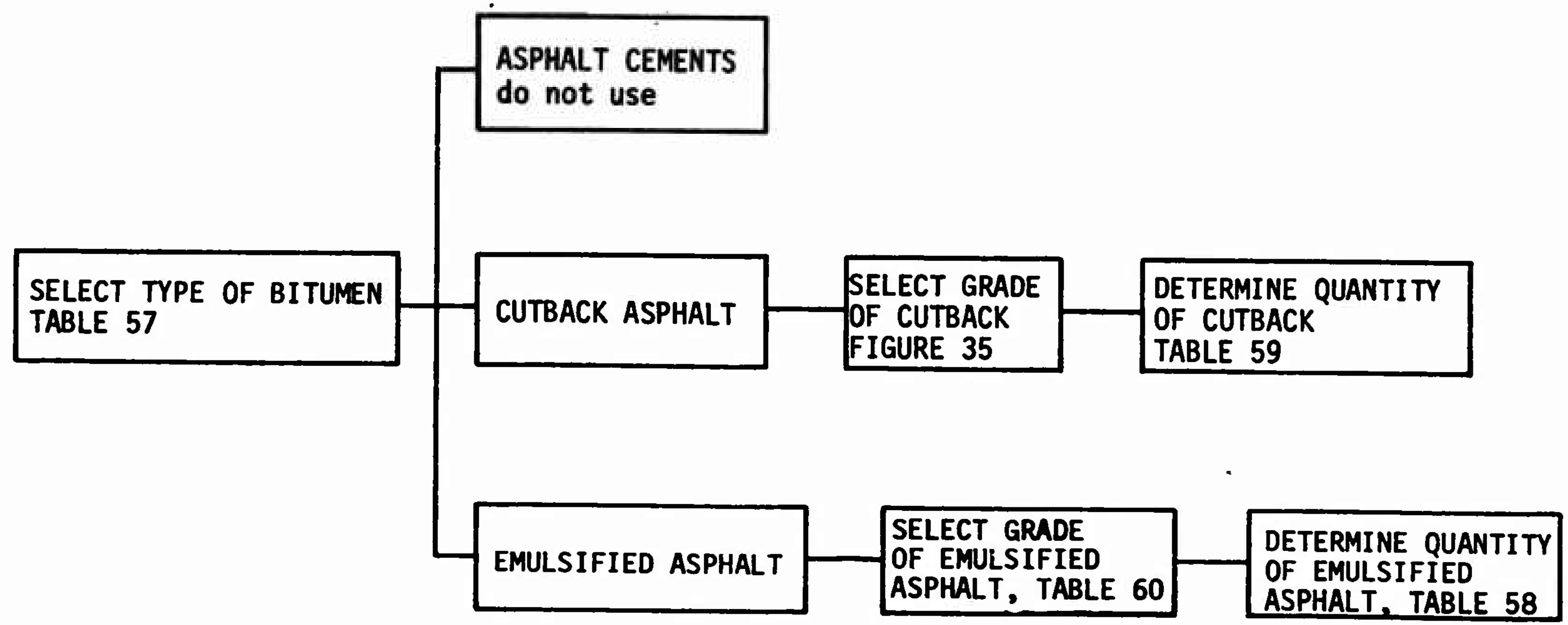


FIGURE 32. SUBSYSTEM FOR EXPEDIENT SUBGRADE STABILIZATION WITH BITUMINOUS MATERIALS

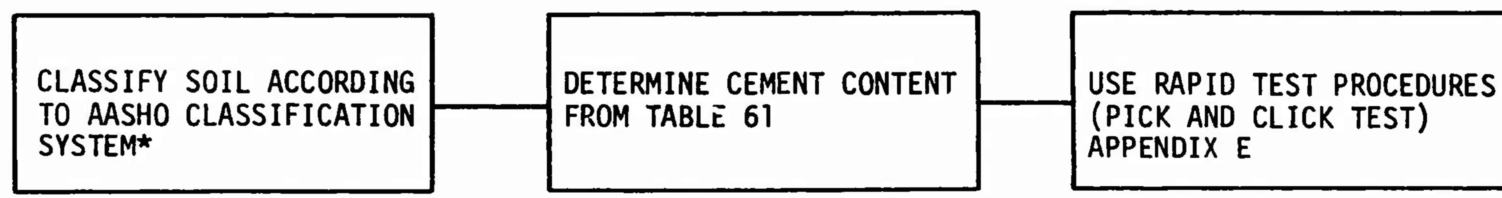


FIGURE 33. SUBSYSTEM FOR EXPEDIENT SUBGRADE STABILIZATION WITH PORTLAND CEMENT

*ALTHOUGH THE UNIFIED CLASSIFICATION SYSTEM CAN BE USED, THE AASHO IS PREFERRED.

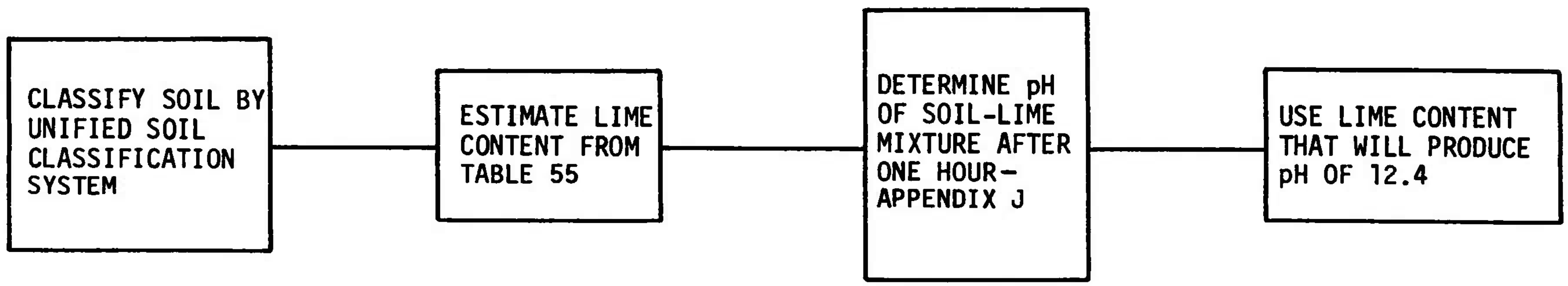
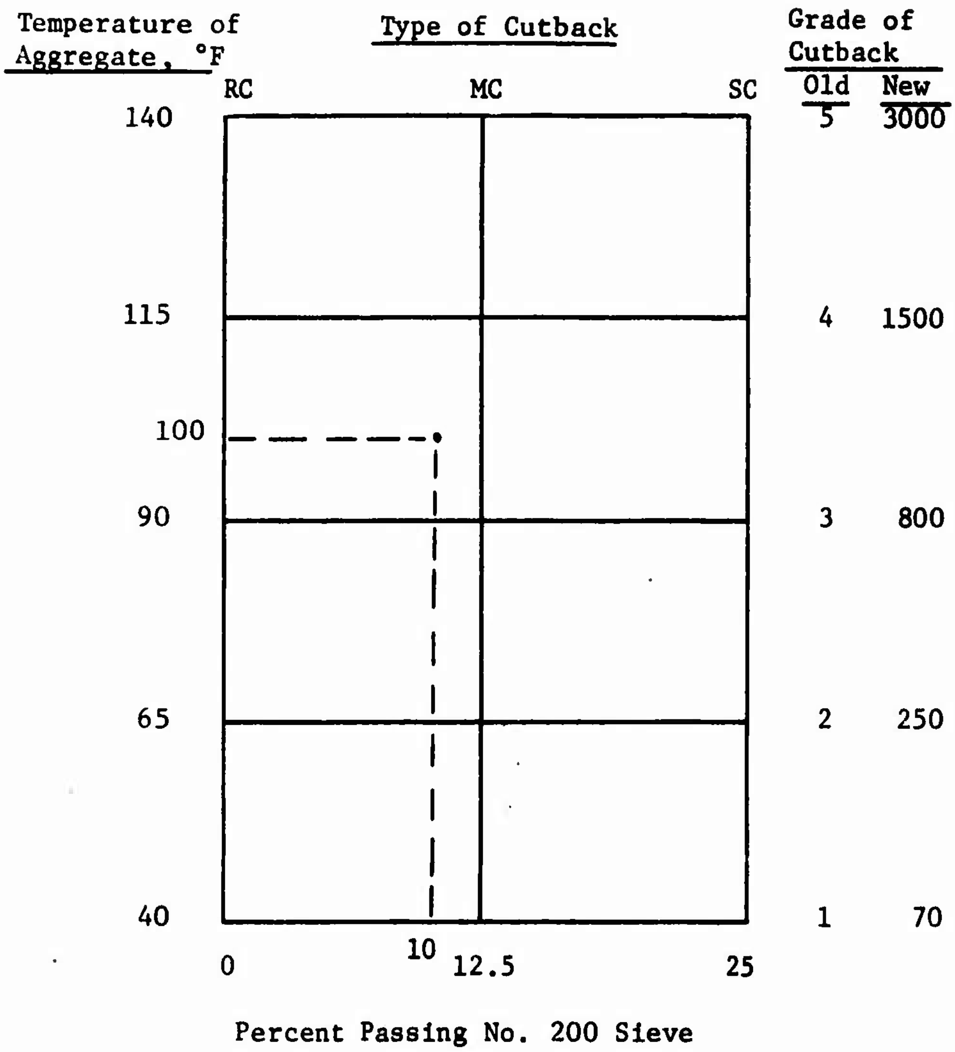


FIGURE 34. SUBSYSTEM FOR EXPEDIENT SUBGRADE STABILIZATION WITH LIME



Example: For aggregate temperature of 100°F and 10% passing #200 sieve, use MC 800 cutback.

FIGURE 35. Selection of type of cutback for stabilization [after U. S. Navy (22)]

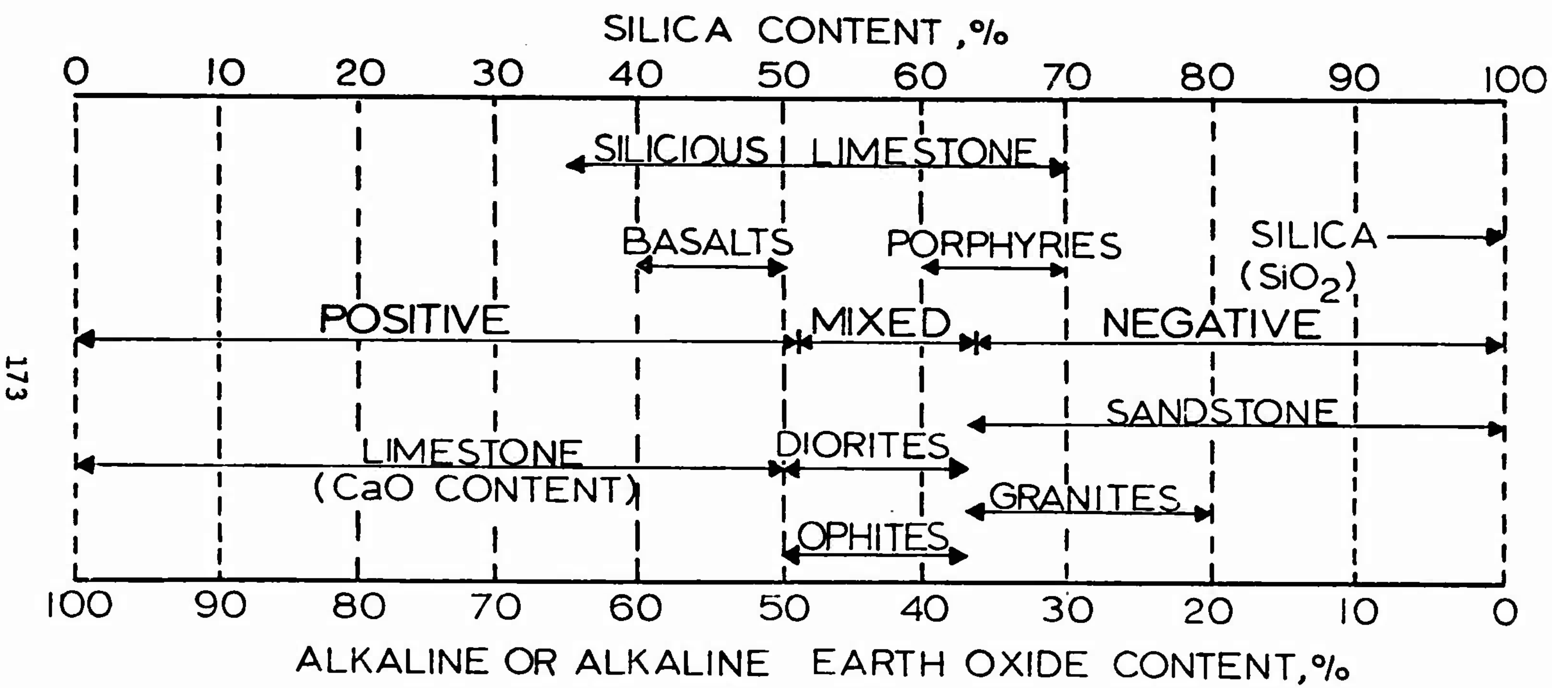


FIGURE 36. Classification of aggregates

[after Mertens and Wright (31)]

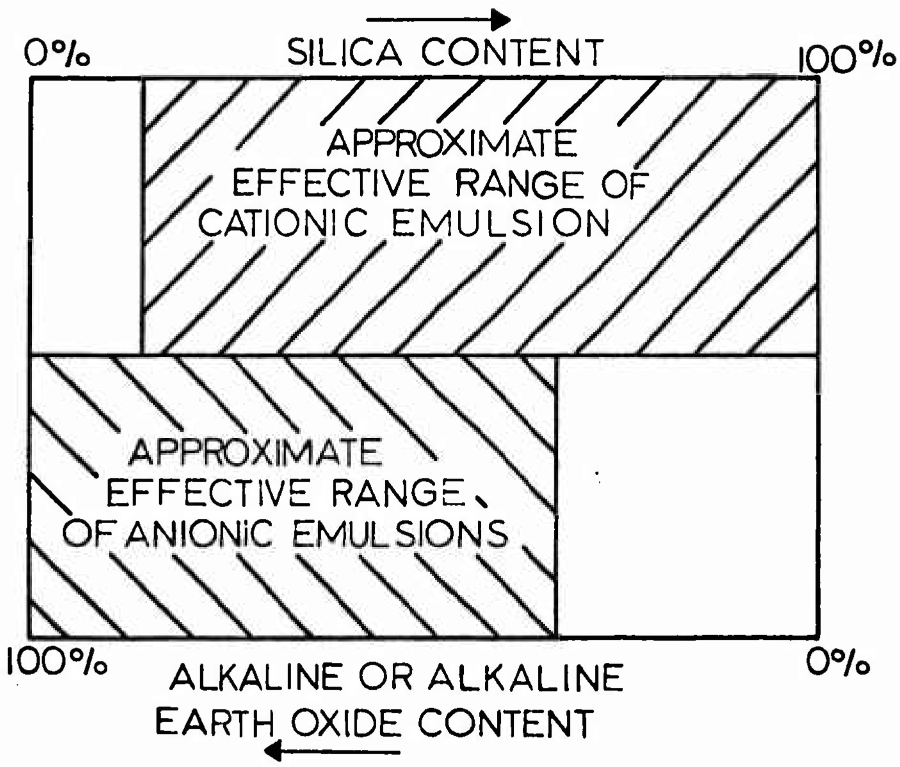


FIGURE 37. **Approximate effective range of cationic and anionic emulsions on various types of aggregates**

[after Mertens and Wright (31)]

TABLE 54

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR BITUMINOUS STABILIZATION IN EXPEDIENT SUBGRADES

Condition	Precautions
Environmental	When asphalt cements are used for bituminous stabilization, proper compaction must be obtained. If thin lifts of asphalt concrete are being placed, the air temperature should be 40°F and rising, and compaction equipment should be used immediately after lay down operation. Adequate compaction can be obtained at freezing temperatures if thick lifts are utilized. When cutbacks and emulsions are utilized, the air temperature and soil temperature should be above freezing. Bituminous materials should completely coat the soil particles before rainfall stops construction.
Construction	Central batch plants together with other specialized equipment, are necessary for bituminous stabilization with asphalt cements. Hot dry weather is preferred for all types of bituminous stabilization.

TABLE 55

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR CEMENT STABILIZATION IN EXPEDIENT SUBGRADES

Condition	Precautions
Environmental	If the soil temperature is less than 40°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and strength gain of the cement-soil mixture will be minimal. If these environmental conditions are expected the cement may act as a modifier.
Construction	If heavy vehicles are allowed on the cement stabilized soils prior to a 10 to 14 day curing period, certain pavement damage can be expected. Construction during periods of heavy rainfall should be avoided. Compaction of cement stabilized soil should be completed within 5 to 6 hours after spreading and mixing.

TABLE 56

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR LIME STABILIZATION IN EXPEDIENT SUBGRADES

Condition	Precautions
Environmental	If the soil temperature is less than 40°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and the strength gain of the lime-soil mixture will be minimal. If these environmental conditions are expected the lime may act as a soil modifier.
Construction	No construction precautions necessary.

TABLE 57

SELECTION OF A SUITABLE TYPE OF BITUMEN

FOR SOIL STABILIZATION PURPOSES

Sand Bitumen	Soil Bitumen	Crushed Stones and Sand-Gravel Bitumen
Hot Mix: Asphalt Cements 60-70 hot climate 85-100 120-150 cold climate		Hot Mix: Asphalt Cements 40-50 hot climate 60-70 85-100 cold climate
Cold Mix: Cutbacks See Figure 35	Cold Mix: Cutbacks See Figure 35	Cold Mix: Cutbacks See Figure 35
Emulsions See Table 60 See Figures 36 and 37 to determine if a catonic or anonic emulsion should be used	Emulsions See Table 60 See Figures 36 and 37 to determine if a catonic or anonic emulsion should be used	Emulsions See Table 60 See Figures 36 and 37 to determine if a catonic or anonic emulsion should be used

TABLE 58

EMULSIFIED ASPHALT REQUIREMENT

Percent passing No. 200	Lbs. of emulsified asphalt per 100 lbs. of dry aggregate when percent passing No. 10 sieve is:					
	50*	60	70	80	90	100
0	6.0	6.3	6.5	6.7	7.0	7.2
2	6.3	6.5	6.7	7.0	7.2	7.5
4	6.5	6.7	7.0	7.2	7.5	7.7
6	6.7	7.0	7.2	7.5	7.7	7.9
8	7.0	7.2	7.5	7.7	7.9	8.2
10	7.2	7.5	7.7	7.9	8.2	8.4
12	7.5	7.7	7.9	8.2	8.4	8.6
14	7.2	7.5	7.7	7.9	8.2	8.4
16	7.0	7.2	7.5	7.7	7.9	8.2
18	6.7	7.0	7.2	7.5	7.7	7.9
20	6.5	6.7	7.0	7.2	7.5	7.7
22	6.3	6.5	6.7	7.0	7.2	7.5
24	6.0	6.3	6.5	6.7	7.0	7.2
25	6.2	6.4	6.6	6.9	7.1	7.3

*50 or less.

[after U. S. Navy (22)]

TABLE 59

DETERMINATION OF QUANTITY OF CUTBACK ASPHALT

$$p = 0.02\ (a) + 0.07\ (b) + 0.15\ (c) + 0.20\ (d)$$

where: p = percent of residual asphalt by weight of dry aggregate.

a = percent of mineral aggregate retained on No. 50 sieve.

b = percent of mineral aggregate passing No. 50 and retained on No. 100 sieve.

c = percent of mineral aggregate passing No. 100 and retained on No. 200 sieve.

d = percent of mineral aggregate passing No. 200 sieve.

TABLE 60

SELECTION OF TYPE OF EMULSIFIED ASPHALT FOR STABILIZATION

Percent Passing # 200 Sieve	Relative Water Content of Soil	
	Wet (5%+)	Dry (0-5%)
0-5	SS-1h (or SS-Kh)	SM-K (or SS-1h*)
5-15	SS-1, SS-1h (or SS-K, SS-Kh)	SM-K (or SS-1h*, SS-1*)
15-25	SS-1 (or SS-K)	SM-K

*Soil should be pre-wetted with water before using these types of emulsified asphalts.

[after U. S. Navy (22)]

TABLE 61

CEMENT REQUIREMENTS FOR VARIOUS SOILS

AASHO Soil Classification	Unified Soil Classification*	Usual Range in cement requirement**		Estimated cement content and that used in moisture-density test, percent by weight	Cement contents for wet-dry and freeze-thaw tests, percent by weight
		percent by vol.	percent by wt.		
A-1-a	GW, GP, GM, SW, SP, SM	5- 7	3- 5	5	3- 5- 7
A-1-b	GM, GP, SM, SP	7- 9	5- 8	6	4- 6- 8
A-2	GM, GC, SM, SC	7-10	5- 9	7	5- 7- 9
A-3	SP	8-12	7-11	9	7- 9-11
A-4	CL, ML	8-12	7-12	10	8-10-12
A-5	ML, MH, OH	8-12	8-13	10	8-10-12
A-6	CL, CH	10-14	9-15	12	10-12-14
A-7	OH, MH, CH	10-14	10-16	13	11-13-15

*based on correlation presented by Air Force (2)

**for most A horizon soils the cement should be increased 4 percentage points, if the soil is dark grey to grey, and 6 percentage points if the soil is black.

[after Portland Cement Association (10)]

TABLE 62

APPROXIMATE LIME CONTENTS

Soil Type	Approximate treatment, percent by soil weight	
	Hydrated Lime	Quicklime
Clayey gravels (GC, GM-GC) (A-2-6, A-2-7)	2-4	2-3
Silty clays (CL) (A-6, A-7-6)	5-10	3-8
Clays (CH) (A-6, A-7-6)	3-8	3-6

[after U. S. Army (95)]

APPENDIX B

EXPEDIENT BASE COURSE STABILIZATION SYSTEM

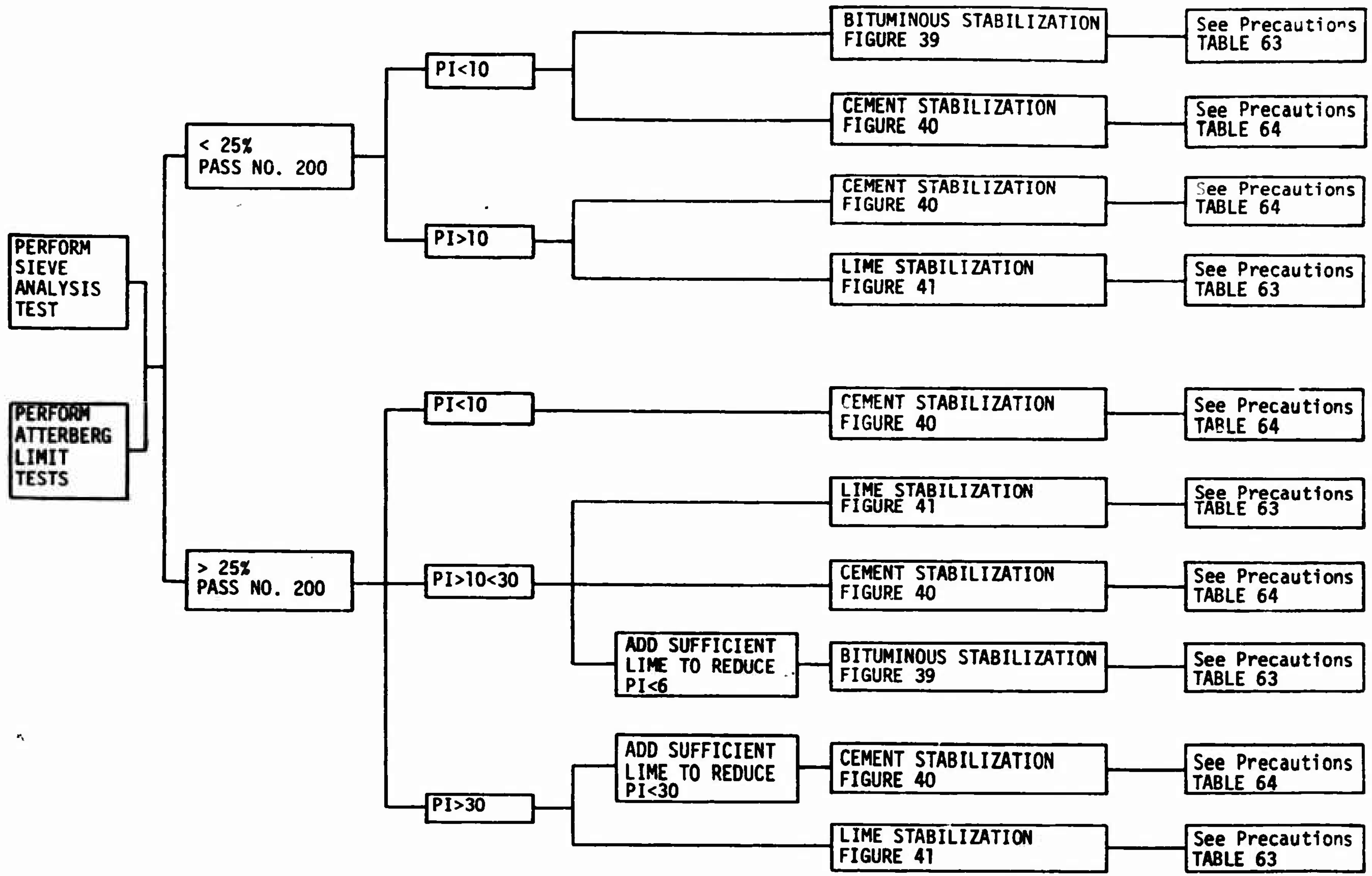


FIGURE 38. SELECTION OF STABILIZER FOR EXPEDIENT BASE CONSTRUCTION

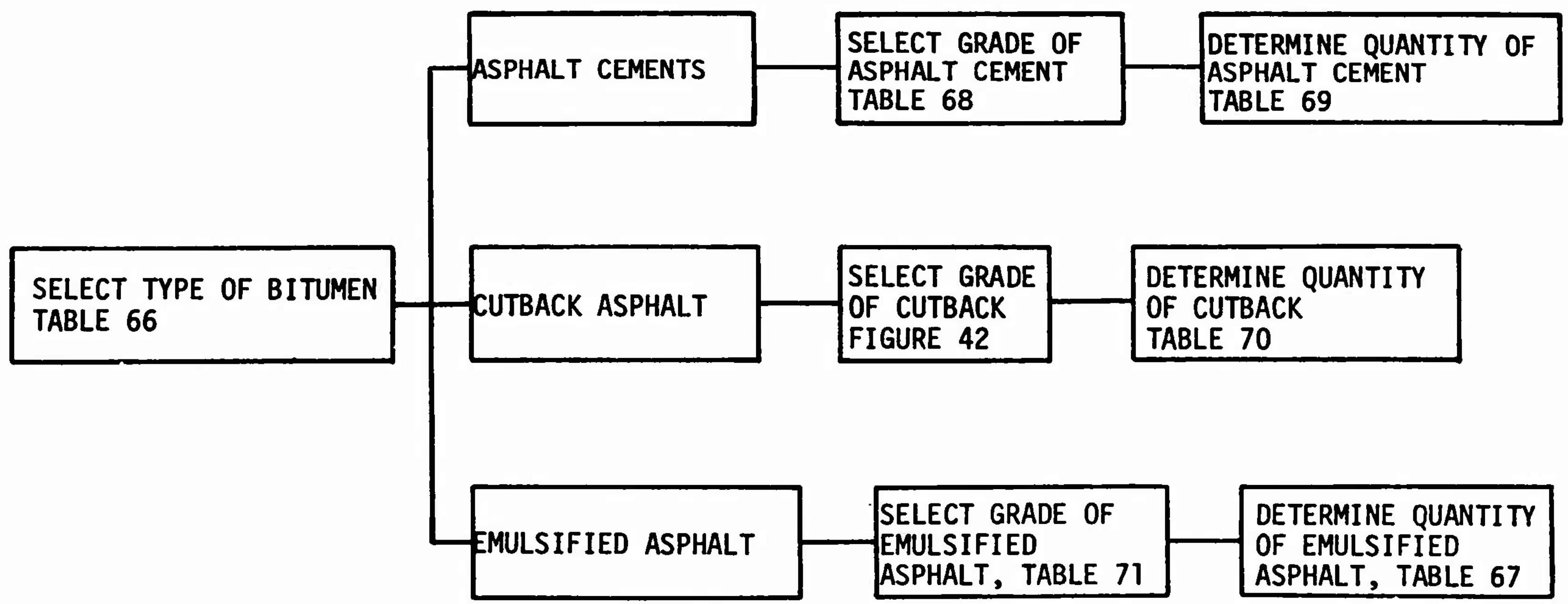


FIGURE 39. SUBSYSTEM FOR EXPEDIENT BASE COURSE STABILIZATION WITH BITUMINOUS MATERIALS

*HARD ASPHALT CEMENTS ARE PREFERRED IN HOT CLIMATES.

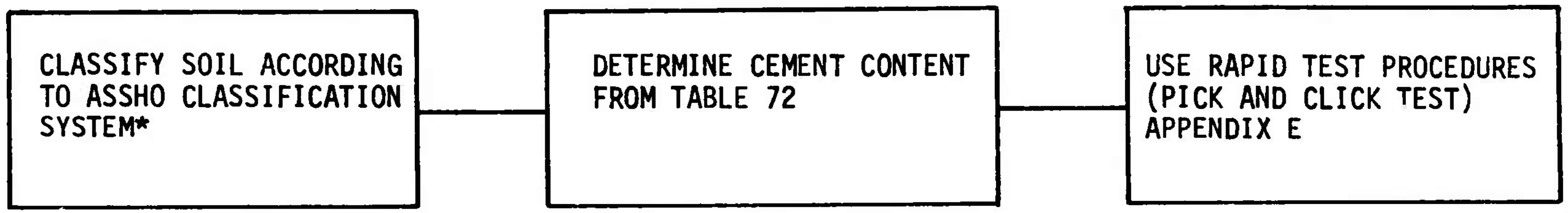


FIGURE 40. SUBSYSTEM FOR EXPEDIENT BASE COURSE STABILIZATION WITH PORTLAND CEMENT

*ALTHOUGH THE UNIFIED CLASSIFICATION SYSTEM CAN BE USED, THE AASHO IS PREFERRED.

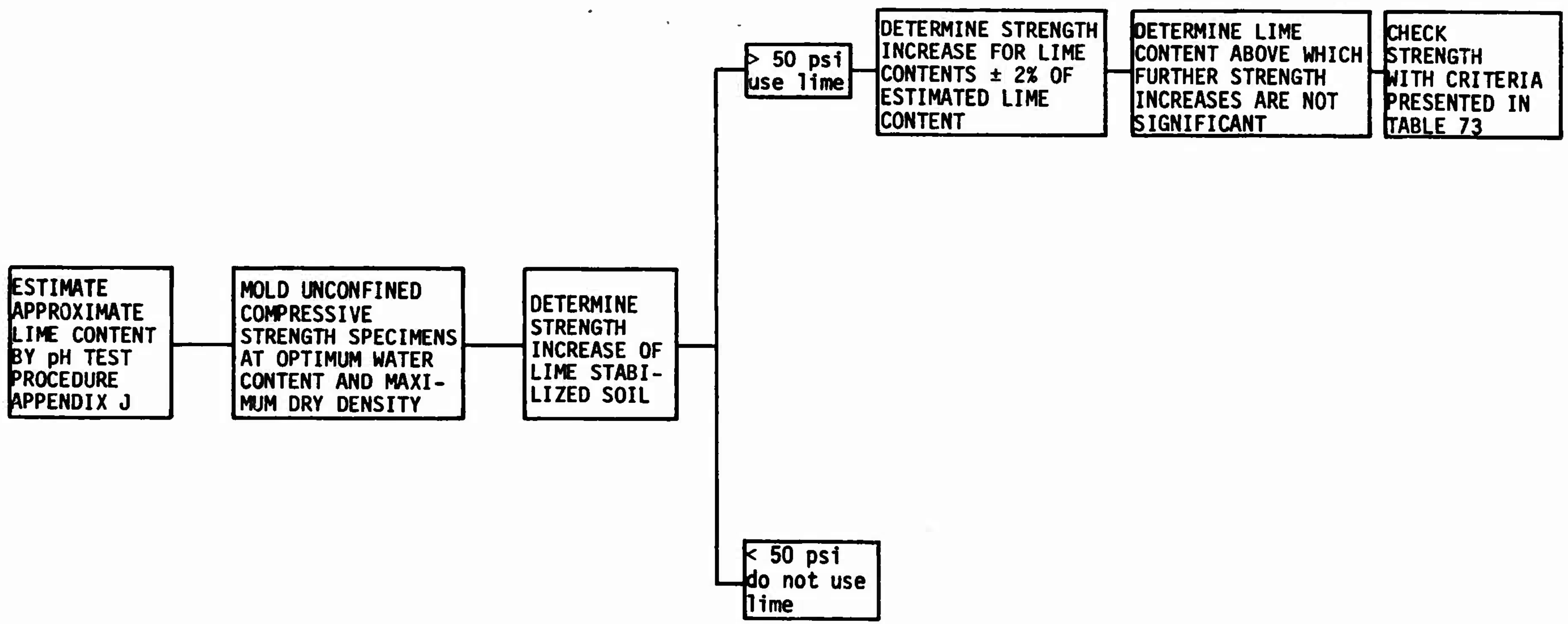
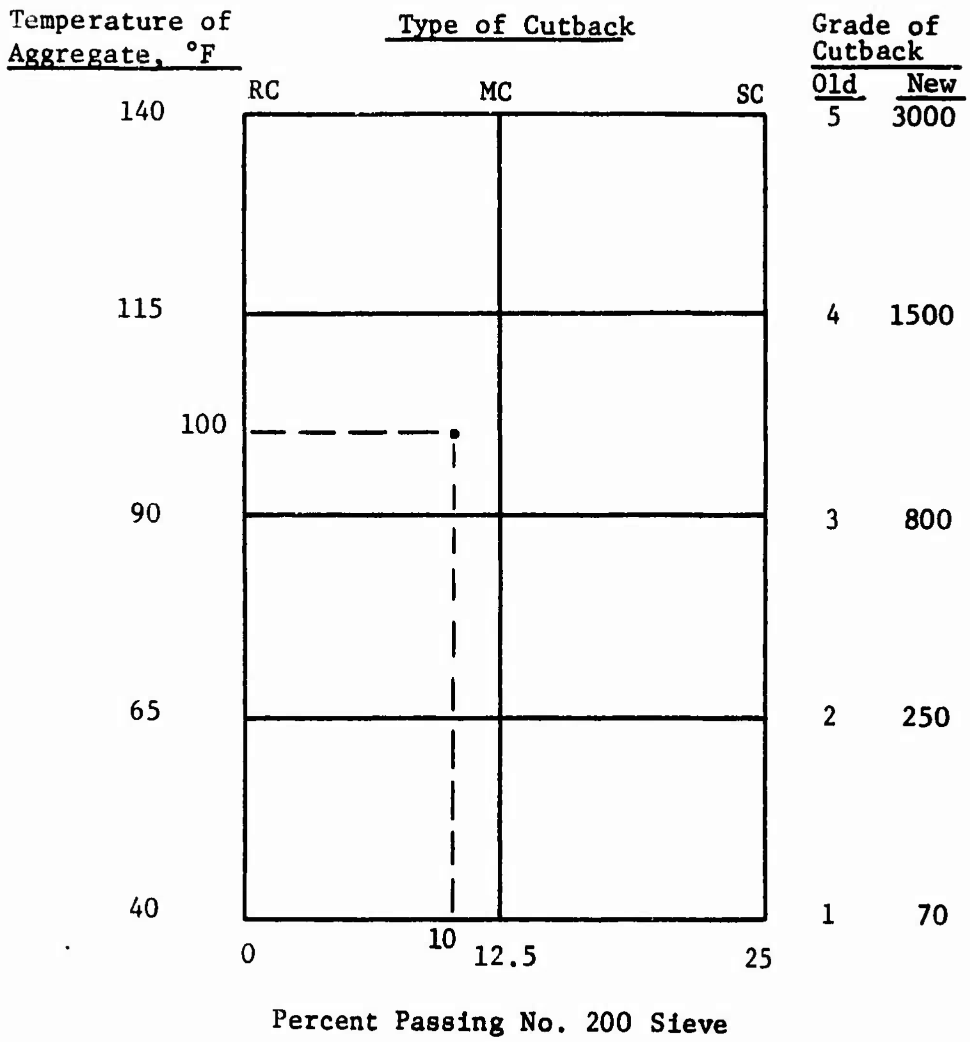


FIGURE 41. SUBSYSTEM FOR EXPEDIENT BASE COURSE STABILIZATION WITH LIME



Example: For aggregate temperature of 100°F and 10% passing #200 sieve, use MC 800 cutback.

FIGURE 42. Selection of type of cutback for stabilization [after U. S. Navy (22)]

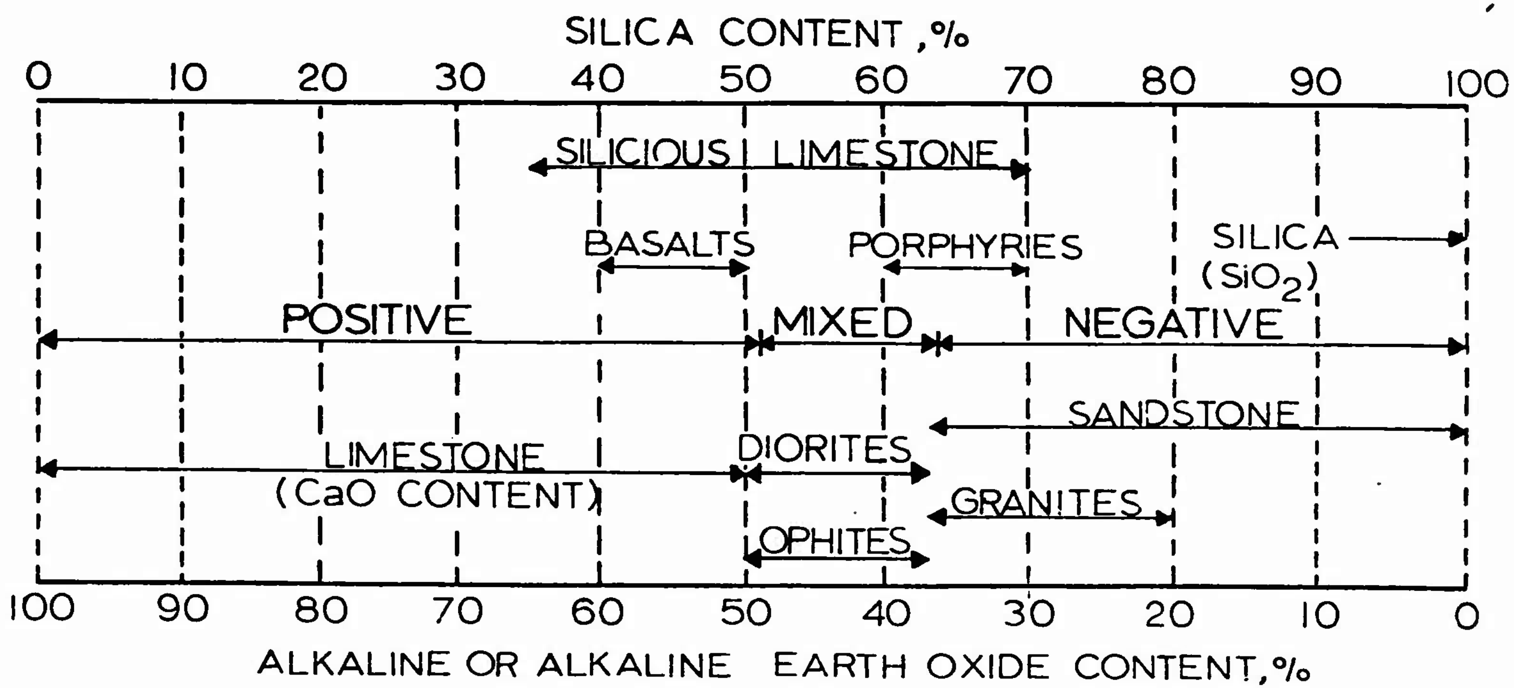


FIGURE 43. Classification of aggregates

[after Mertens and Wright (31)]

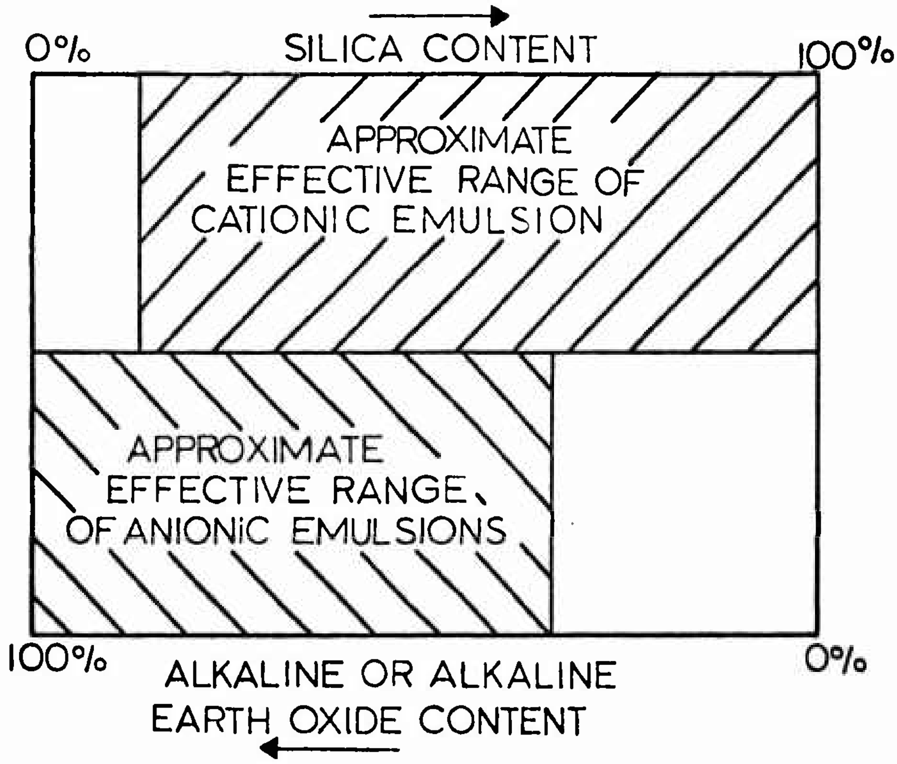


FIGURE 44. Approximate effective range of cationic and anionic emulsions on various types of aggregates

[after Mertens and Wright (31)]

TABLE 63

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR BITUMINOUS STABILIZATION IN EXPEDIENT BASE COURSES

Condition	Precautions
Environmental	When asphalt cements are used for bituminous stabilization, proper compaction must be obtained. If thin lifts of asphalt concrete are being placed, the air temperature should be 40°F and rising, and compaction equipment should be used immediately after lay down operation. Adequate compaction can be obtained at freezing temperatures if thick lifts are utilized. When cutbacks and emulsions are utilized, the air temperature and soil temperature should be above freezing. Bituminous materials should completely coat the soil particles before rainfall stops construction.
Construction	Central batch plants together with other specialized equipment, are necessary for bituminous stabilization with asphalt cements. Hot dry weather is preferred for all types of bituminous stabilization.

TABLE 64

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR CEMENT STABILIZATION IN EXPEDIENT BASE COURSES

Condition	Precautions
Environmental	If the soil temperature is less than 60 to 70°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and strength gain of the cement-soil mixture will be minimal. If these environmental conditions are expected, an alternative stabilizer should be investigated for possible use.
Construction	If heavy vehicles are allowed on the cement stabilized soils prior to a 10 to 14 day curing period, certain pavement damage can be expected.

TABLE 65

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR LIME STABILIZATION IN EXPEDIENT BASE COURSES

Condition	Precautions
Environmental	If the soil temperature is less than 60 to 70°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and the strength gain of the lime-soil mixture will be minimal. If these environmental conditions are expected an alternative stabilizer should be investigated for possible use.
Construction	If heavy vehicles are allowed on the lime stabilized soils prior to a 10 to 14 day curing period, certain pavement damage can be expected.

TABLE 66

SELECTION OF A SUITABLE TYPE OF BITUMEN

FOR SOIL STABILIZATION PURPOSES

Sand Bitumen	Soil Bitumen	Crushed Stones and Sand-Gravel Bitumen
Hot Mix: Asphalt Cements 60-70 hot climate 85-100 120-150 cold climate		Hot Mix: Asphalt Cements 40-50 hot climate 60-70 85-100 cold climate
Cold Mix: Cutbacks See Figure 42 Emulsions See Table 71 See Figures 43 and 44 to determine if a catonic or anonic emulsion should be used	Cold Mix: Cutbacks See Figure 42 Emulsions See Table 71 See Figures 43 and 44 to determine if a catonic or anonic emulsion should be used	Cold Mix: Cutbacks See Figure 42 Emulsions See Table 71 See Figures 43 and 44 to determine if a catonic or anonic emulsion should be used

TABLE 67

EMULSIFIED ASPHALT REQUIREMENT

Percent passing No. 200	Lbs. of emulsified asphalt per 100 lbs. of dry aggregate when percent passing No. 10 sieve is:					
	50*	60	70	80	90	100
0	6.0	6.3	6.5	6.7	7.0	7.2
2	6.3	6.5	6.7	7.0	7.2	7.5
4	6.5	6.7	7.0	7.2	7.5	7.7
6	6.7	7.0	7.2	7.5	7.7	7.9
8	7.0	7.2	7.5	7.7	7.9	8.2
10	7.2	7.5	7.7	7.9	8.2	8.4
12	7.5	7.7	7.9	8.2	8.4	8.6
14	7.2	7.5	7.7	7.9	8.2	8.4
16	7.0	7.2	7.5	7.7	7.9	8.2
18	6.7	7.0	7.2	7.5	7.7	7.9
20	6.5	6.7	7.0	7.2	7.5	7.7
22	6.3	6.5	6.7	7.0	7.2	7.5
24	6.0	6.3	6.5	6.7	7.0	7.2
25	6.2	6.4	6.6	6.9	7.1	7.3

*50 or less.

[after U. S. Navy (22)]

TABLE 68

DETERMINATION OF ASPHALT GRADE FOR

BASE COURSE STABILIZATION

Pavement Temperature Index*	Asphalt Grade, Penetration
Negative	100-120
0-40	85-100
40-100	60-70
Above 100	40-50

*The sum, for a 1 - year period, of the increments above 75°F of monthly averages of the daily maximum temperatures. Average daily maximum temperatures for the period of record should be used where 10 or more years of record are available. For records of less than 10-year duration the record for the hottest year should be used. A negative index results when no monthly average exceeds 75°F. Negative indexes are evaluated merely by subtracting the largest monthly average from 75°F.

TABLE 69

SELECTION OF ASPHALT CEMENT CONTENT

FOR EXPEDIENT BASE COURSE CONSTRUCTION

Aggregate Shape and Surface Texture	Percent Asphalt by Weight of Dry Aggregate*
Rounded and Smooth	4
Angular and Rough	6
Intermediate	5

*Approximate quantities which may be adjusted in field based on observation of mix and engineering judgment.

TABLE 70

DETERMINATION OF QUANTITY OF CUTBACK ASPHALT

$$p = 0.02\ (a) + 0.07\ (b) + 0.15\ (c) + 0.20\ (d)$$

where: p = percent of residual asphalt by weight of dry aggregate.

a = percent of mineral aggregate retained on No. 50 sieve.

b = percent of mineral aggregate passing No. 50 and retained on No. 100 sieve.

c = percent of mineral aggregate passing No. 100 and retained on No. 200 sieve.

d = percent of mineral aggregate passing No. 200 sieve.

TABLE 71

SELECTION OF TYPE OF EMULSIFIED ASPHALT FOR STABILIZATION

Percent Passing # 200 Sieve	Relative Water Content of Soil	
	Wet (5%+)	Dry (0-5%)
0-5	SS-1h (or SS-Kh)	SM-K (or SS-1h*)
5-15	SS-1, SS-1h (or SS-K, SS-Kh)	SM-K (or SS-1h*, SS-1*)
15-25	SS-1 (or SS-K)	SM-K

*Soil should be pre-wetted with water before using these types of emulsified asphalts.

[after U. S. Navy (22)]

TABLE 72

CEMENT REQUIREMENTS FOR VARIOUS SOILS

AASHO Soil Classification	Unified Soil Classification*	Usual Range in cement requirement**		Estimated cement content and that used in moisture-density test, percent by weight	Cement contents for wet-dry and freeze-thaw tests, percent by weight
		percent by vol.	percent by wt.		
A-1-a	GW, GP, GM, SW, SP, SM	5- 7	3- 5	5	3- 5- 7
A-1-b	GM, GP, SM, SP	7- 9	5- 8	6	4- 6- 8
A-2	GM, GC, SM, SC	7-10	5- 9	7	5- 7- 9
A-3	SP	8-12	7-11	9	7- 9-11
A-4	CL, ML	8-12	7-12	10	8-10-12
A-5	ML, MH, OH	8-12	8-13	10	8-10-12
A-6	CL, CH	10-14	9-15	12	10-12-14
A-7	OH, MH, CH	10-14	10-16	13	11-13-15

*based on correlation presented by Air Force (2)

**for most A horizon soils the cement should be increased 4 percentage points, if the soil is dark grey to grey, and 6 percentage points if the soil is black.

[after Portland Cement Association (10)]

TABLE 73

TENTATIVE LIME-SOIL MIXTURE COMPRESSIVE STRENGTH REQUIREMENTS

Anticipated Use	Residual Strength Requirement, psi (a)	Strength Requirements for Various Anticipated Service Conditions (b)			
		Extended (8 day) Soaking (psi)	Cyclic Freeze-Thaw (e) 3 Cycles (psi)	7 Cycles (psi)	10 Cycles (psi)
Modified Subgrade	20	50	50	90 50*	120
Subbase					
Rigid Pavement	20	50	50	90 50*	120
Flexible Pavement					
Thickness of Cover (c)					
10 inches	30	60	60	100 60*	130
8 inches	40	70	70	110 75*	140
5 inches	60	90	90	130 100*	160
Base	100[d]	130	130	170 150*	200

a) Minimum anticipated strength following first winter exposure.

b) Strength required at termination of field curing (following construction) to provide adequate residual strength.

c) Total pavement thickness overlying the subbase. The requirements are based on the Boussinesq stress distribution. Rigid pavement requirements apply if cemented materials are used as base courses.

d) Flexural strength should be considered in thickness design.

e) Number of freeze-thaw cycles expected in the lime-soil layer during the first winter of service.

*Note: Freeze-thaw strength losses based on 10 psi/cycle except for 7 cycle values indicated by an * which were based on a previously established regression equation.

[after Thompson (92)]

APPENDIX C

NONEXPEDIENT SUBGRADE STABILIZATION SYSTEM

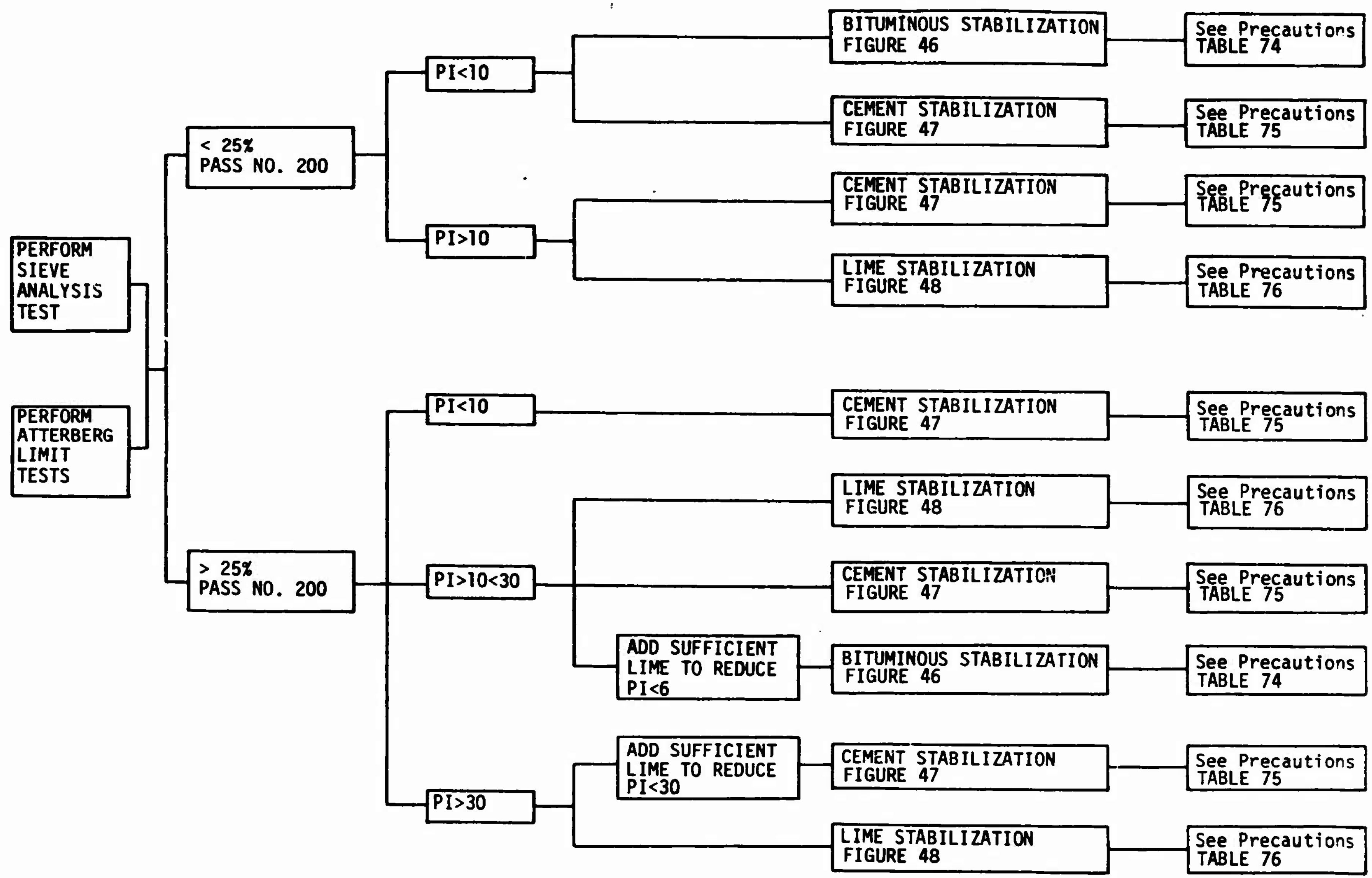


FIGURE 45. SELECTION OF STABILIZER FOR NONEXPEDIENT SUBGRADE CONSTRUCTION

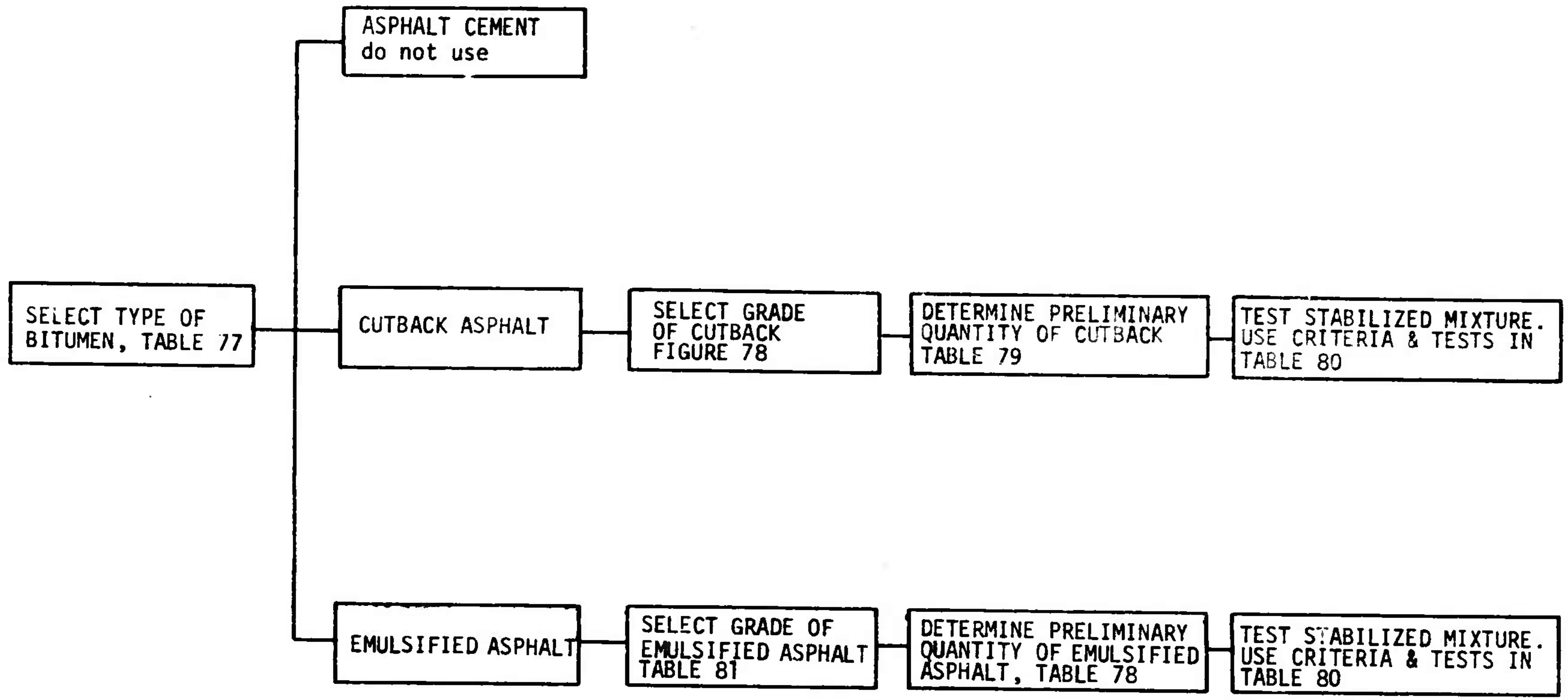


FIGURE 46. SUBSYSTEM FOR NON-EXPEDIENT SUBGRADE STABILIZATION WITH BITUMINOUS MATERIALS

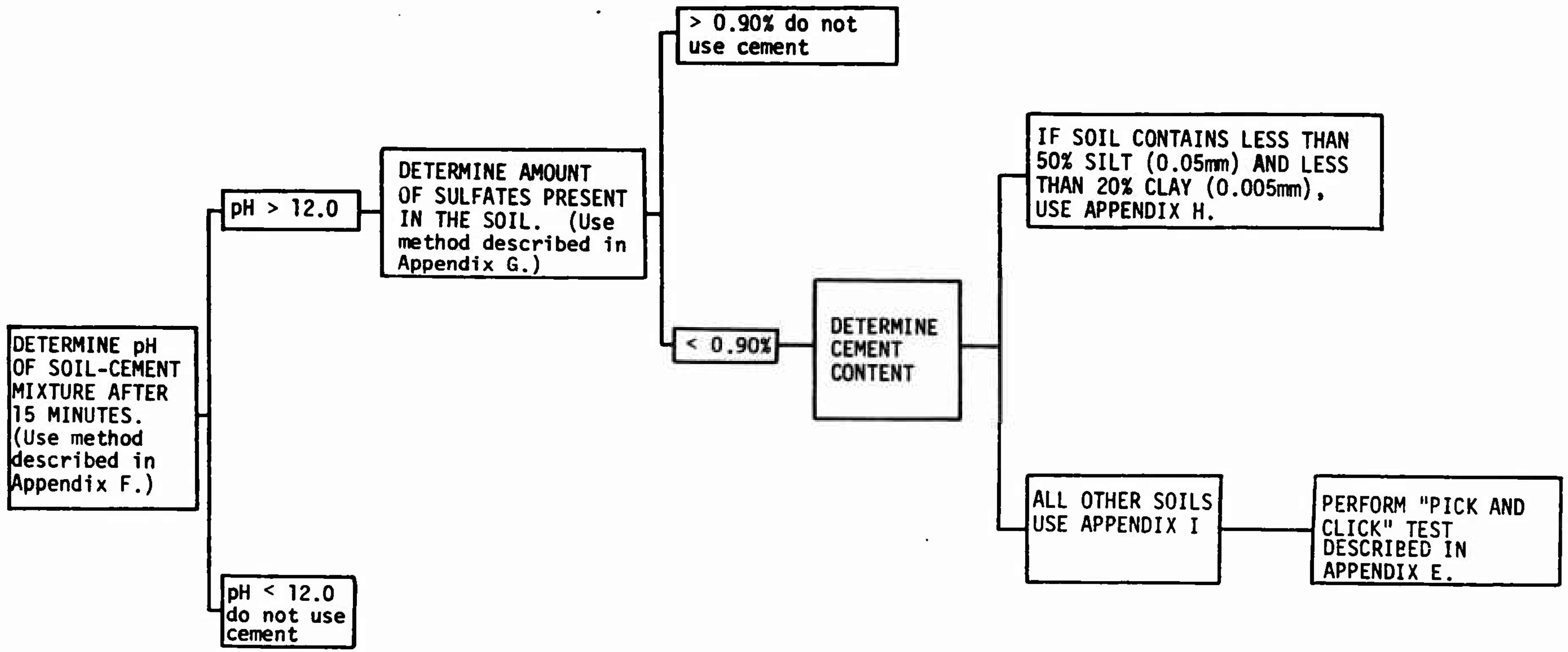


FIGURE 47. SUBSYSTEM FOR NON-EXPEDIENT SUBGRADE STABILIZATION WITH CEMENT

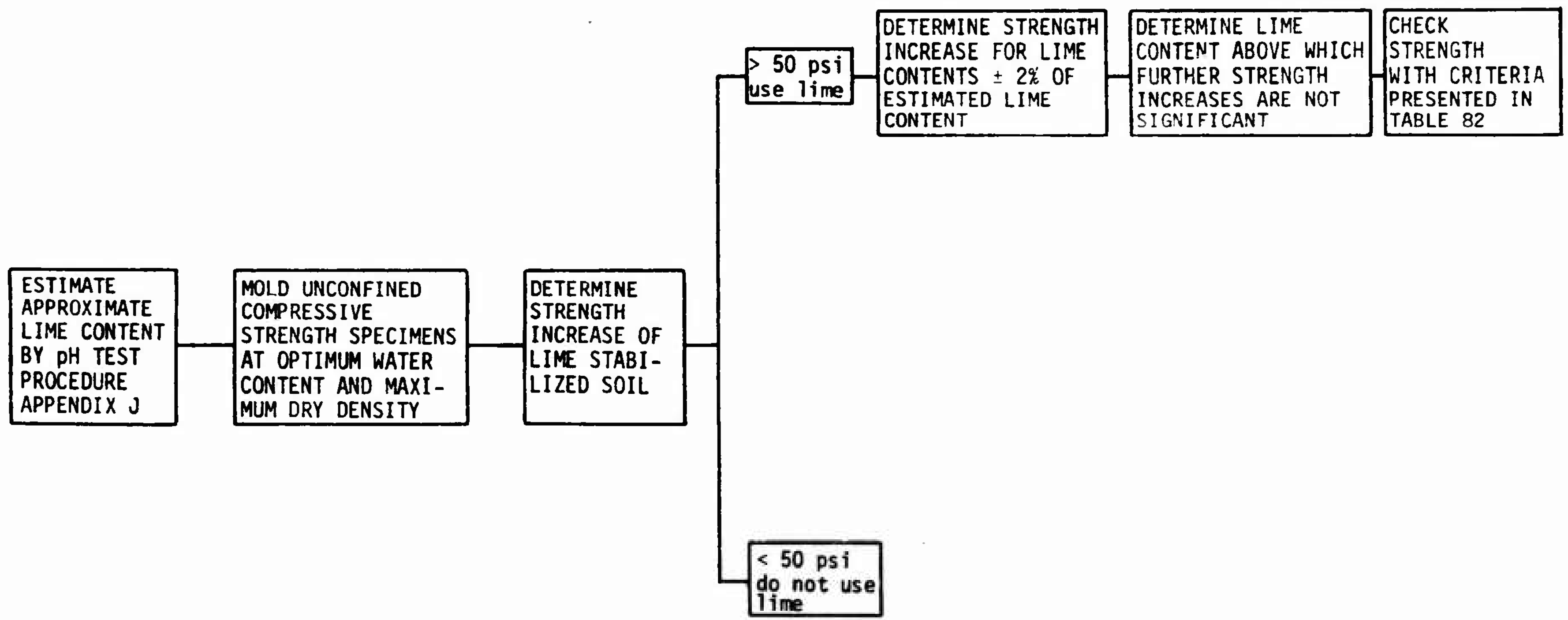
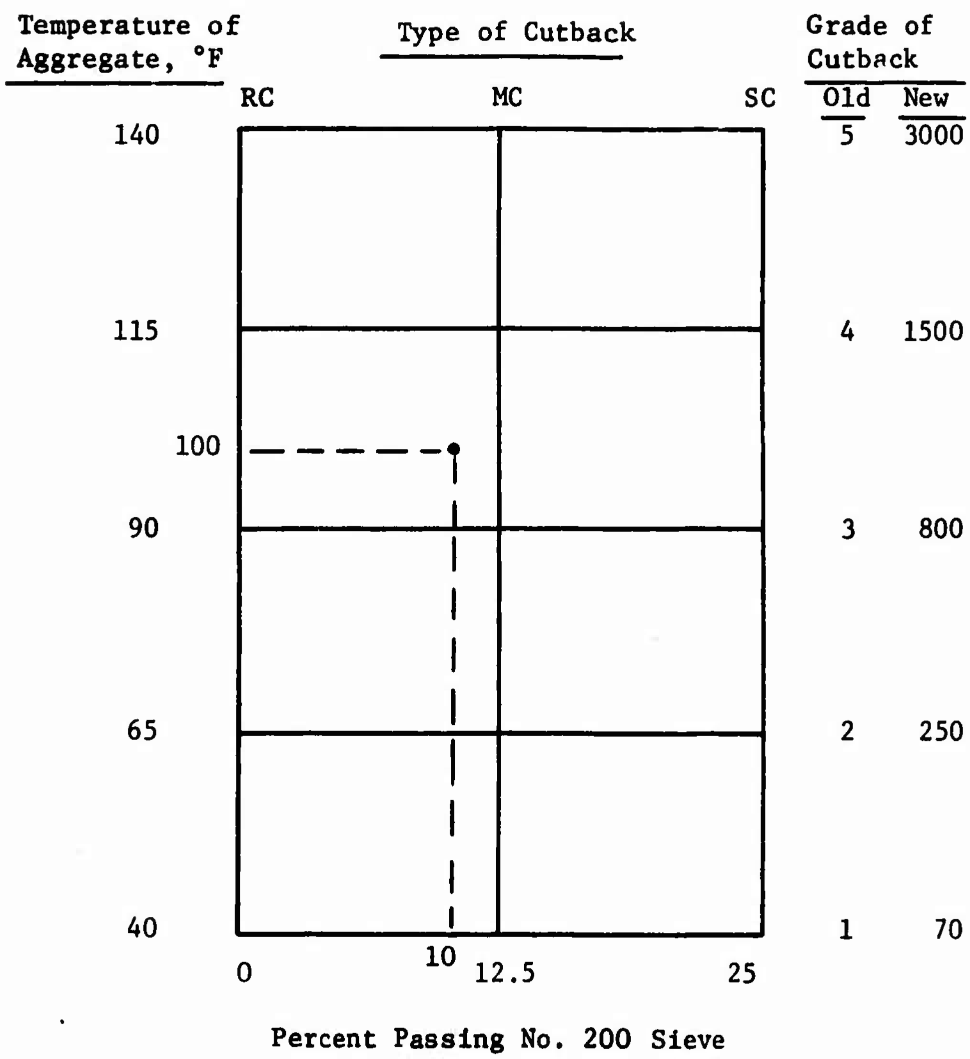


FIGURE 48. SUBSYSTEM FOR NON-EXPEDIENT SUBGRADE STABILIZATION WITH LIME



Example: For aggregate temperature of 100°F and 10% passing #200 sieve, use MC 800 cutback.

FIGURE 49. Selection of type of cutback for stabilization

[after U. S. Navy (22)]

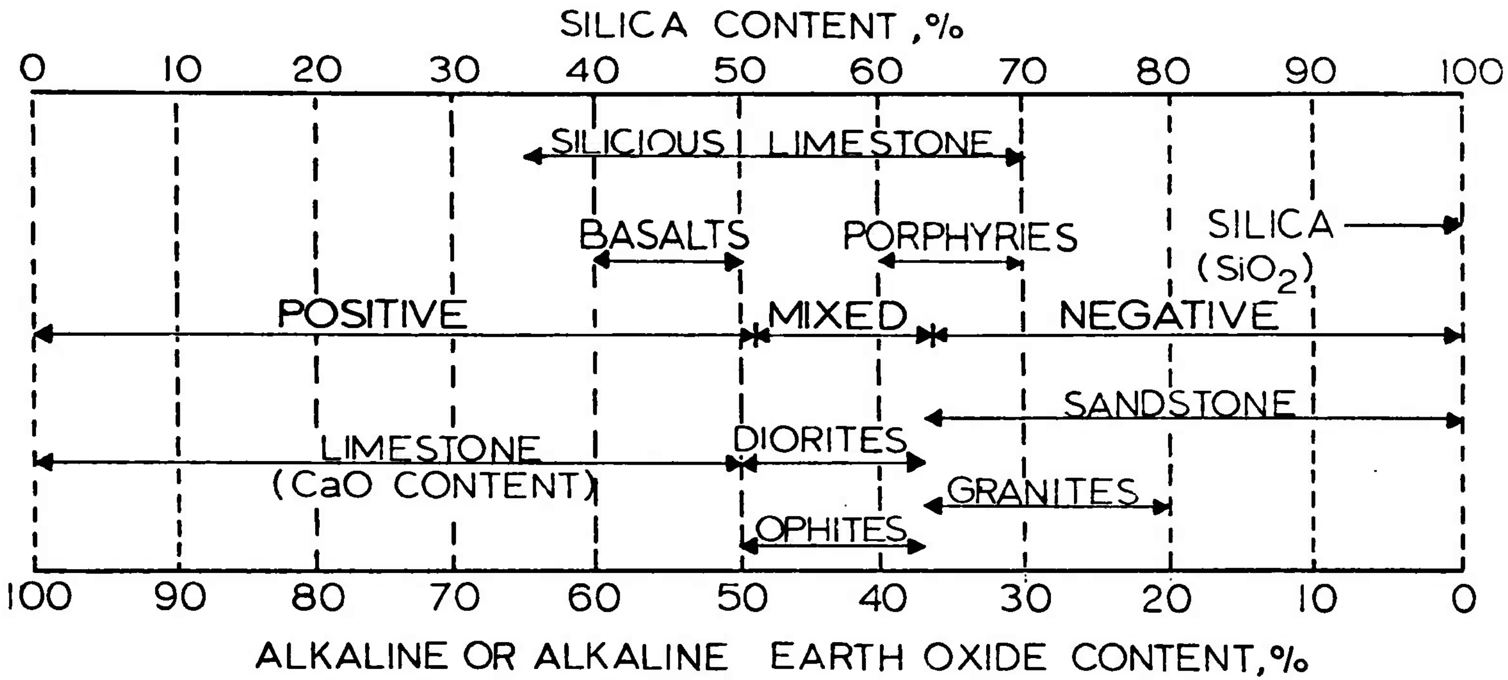


FIGURE 50. Classification of aggregates

[after Mertens and Wright (31)]

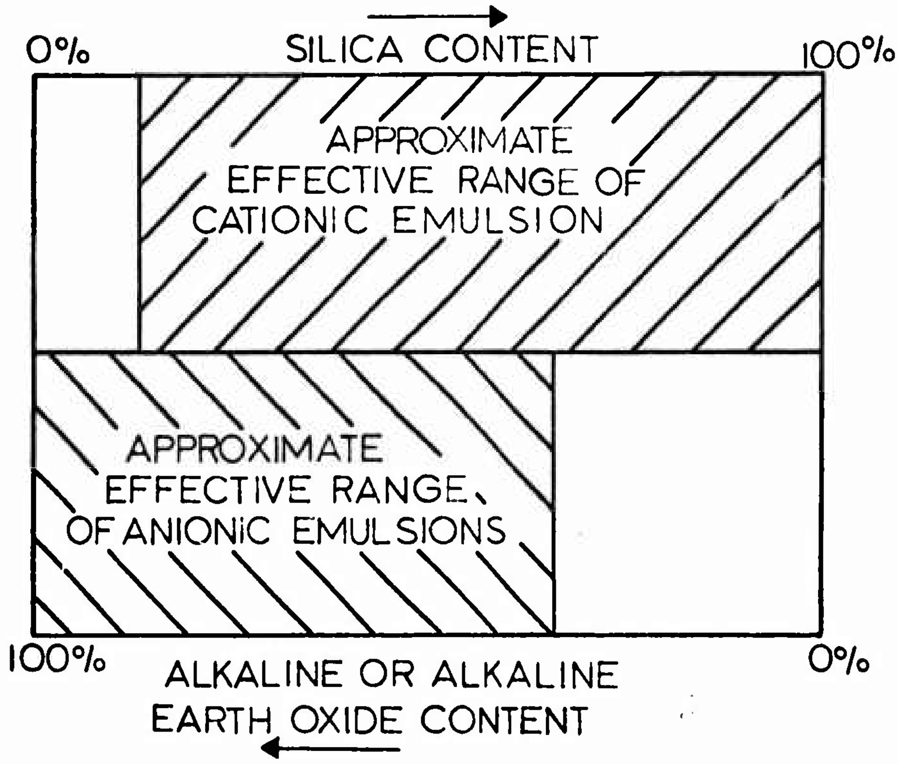


FIGURE 51. Approximate effective range of cationic and anionic emulsions on various types of aggregates

[after Mertens and Wright (31)]

TABLE 74

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR BITUMINOUS STABILIZATION IN NONEXPEDIENT SUBGRADES

Condition	Precautions
Environmental	When asphalt cements are used for bituminous stabilization, proper compaction must be obtained. If thin lifts of asphalt concrete are being placed, the air temperature should be 40°F and rising, and compaction equipment should be used immediately after lay down operation. Adequate compaction can be obtained at freezing temperatures if thick lifts are utilized. When cutbacks and emulsions are utilized, the air temperature and soil temperature should be above freezing. Bituminous materials should completely coat the soil particles before rainfall stops construction.
Construction	Central batch plants, together with other specialized equipment, are necessary for bituminous stabilization with asphalt cements. Hot dry weather is preferred for all types of bituminous stabilization.

TABLE 75

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR CEMENT STABILIZATION IN NONEXPEDIENT SUBGRADES

Condition	Precautions
Environmental	If the soil temperature is less than 60 to 70°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and strength gain of the cement-soil mixture will be minimal. If these environmental conditions are expected the cement may act as a soil modifier. Cement-soil mixtures should be scheduled for construction such that sufficient durability will be gained to resist any freeze-thaw cycles expected.
Construction	If heavy vehicles are allowed on the cement stabilized soils prior to a 10 to 14 day curing period, certain pavement damage can be expected.

TABLE 76

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR LIME STABILIZATION IN NONEXPEDIENT SUBGRADES

Condition	Precautions
Environmental	If the soil temperature is less than 60 to 70°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and the strength gain of the lime-soil mixture will be minimal. If these environmental conditions are expected the lime may act as a soil modifier. Lime-soil mixtures should be scheduled for construction such that sufficient durability will be gained to resist any freeze-thaw cycles expected.
Construction	If heavy vehicles are allowed on the lime stabilized soils prior to a 10 to 14 day curing period, certain pavement damage can be expected.

TABLE 77

SELECTION OF A SUITABLE TYPE OF BITUMEN

FOR SOIL STABILIZATION PURPOSES

Sand Bitumen	Soil Bitumen	Crushed Stones and Sand-Gravel Bitumen
Hot Mix: Asphalt Cements 60-70 hot climate 85-100 120-150 cold climate		Hot Mix: Asphalt Cements 40-50 hot climate 60-70 85-100 cold climate
Cold Mix: Cutbacks See Figure 49 Emulsions See Table 81 See Figures 50 and 51 to determine if a catonic or anonic emulsion should be used	Cold Mix: Cutbacks See Figure 49 Emulsions See Table 81 See Figures 50 and 51 to determine if a catonic or anonic emulsion should be used	Cold Mix: Cutbacks See Figure 49 Emulsions See Table 81 See Figures 50 and 51 to determine if a catonic or anonic emulsion should be used

TABLE 78

EMULSIFIED ASPHALT REQUIREMENT

Percent passing No. 200	Lbs. of emulsified asphalt per 100 lbs. of dry aggregate when percent passing No. 10 sieve is:					
	50*	60	70	80	90	100
0	6.0	6.3	6.5	6.7	7.0	7.2
2	6.3	6.5	6.7	7.0	7.2	7.5
4	6.5	6.7	7.0	7.2	7.5	7.7
6	6.7	7.0	7.2	7.5	7.7	7.9
8	7.0	7.2	7.5	7.7	7.9	8.2
10	7.2	7.5	7.7	7.9	8.2	8.4
12	7.5	7.7	7.9	8.2	8.4	8.6
14	7.2	7.5	7.7	7.9	8.2	8.4
16	7.0	7.2	7.5	7.7	7.9	8.2
18	6.7	7.0	7.2	7.5	7.7	7.9
20	6.5	6.7	7.0	7.2	7.5	7.7
22	6.3	6.5	6.7	7.0	7.2	7.5
24	6.0	6.3	6.5	6.7	7.0	7.2
25	6.2	6.4	6.6	6.9	7.1	7.3

*50 or less.

[after U. S. Navy (22)]

TABLE 79

DETERMINATION OF QUANTITY OF CUTBACK ASPHALT

$$p = 0.02\,(a) + 0.07\,(b) + 0.15\,(c) + 0.20\,(d)$$

where: p = percent of residual asphalt by weight of dry aggregate.

a = percent of mineral aggregate retained on No. 50 sieve.

b = percent of mineral aggregate passing No. 50 and retained on No. 100 sieve.

c = percent of mineral aggregate passing No. 100 and retained on No. 200 sieve.

d = percent of mineral aggregate passing No. 200 sieve.

TABLE 80

MARSHALL MIX DESIGN CRITERIA FOR

CUTBACK AND EMULSIFIED ASPHALT MIXTURES

Marshall Test	Criteria for a Test Temperature of 77°F	
	Minimum	Maximum
Stability, lbs.	750	---
Flow, (0.01 in.)	7	16
Percent air voids	3	5

[after Lefebvre (49)]

TABLE 81

SELECTION OF TYPE OF EMULSIFIED ASPHALT FOR STABILIZATION

Percent Passing # 200 Sieve	Relative Water Content of Soil	
	Wet (5%+)	Dry (0-5%)
0-5	SS-1h (or SS-Kh)	SM-K (or SS-1h*)
5-15	SS-1, SS-1h (or SS-K, SS-Kh)	SM-K (or SS-1h*, SS-1*)
15-25	SS-1 (or SS-K)	SM-K

*Soil should be pre-wetted with water before using these types of emulsified asphalts.

[after U. S. Navy (22)]

TABLE 82

TENTATIVE LIME-SOIL MIXTURE COMPRESSIVE STRENGTH REQUIREMENTS

Anticipated Use	Residual Strength Requirement, psi (a)	Strength Requirements for Various Anticipated Service Conditions (b)			
			Cyclic Freeze-Thaw (e)		
		Extended (8 day) Soaking (psi)	3 Cycles (psi)	7 Cycles (psi)	10 Cycles (psi)
Modified Subgrade	20	50	50	90 50*	120
Subbase					
Rigid Pavement	20	50	50	90 50*	120
Flexible Pavement					
Thickness of Cover (c)					
10 inches	30	60	60	100 60*	130
8 inches	40	70	70	110 75*	140
5 inches	60	90	90	130 100*	160
Base	100 (d)	130	130	170 150*	200

a) Minimum anticipated strength following first winter exposure.

b) Strength required at termination of field curing (following construction) to provide adequate residual strength.

c) Total pavement thickness overlying the subbase. The requirements are based on the Boussinesq stress distribution. Rigid pavement requirements apply if cemented materials are used as base courses.

d) Flexural strength should be considered in thickness design.

e) Number of freeze-thaw cycles expected in the lime-soil layer during the first winter of service.

*Note: Freeze-thaw strength losses based on 10 psi/cycle except for 7 cycle values indicated by an * which were based on a previously established regression equation.

[after Thompson (92)]

APPENDIX D

NONEXPEDIENT BASE COURSE STABILIZATION SYSTEM

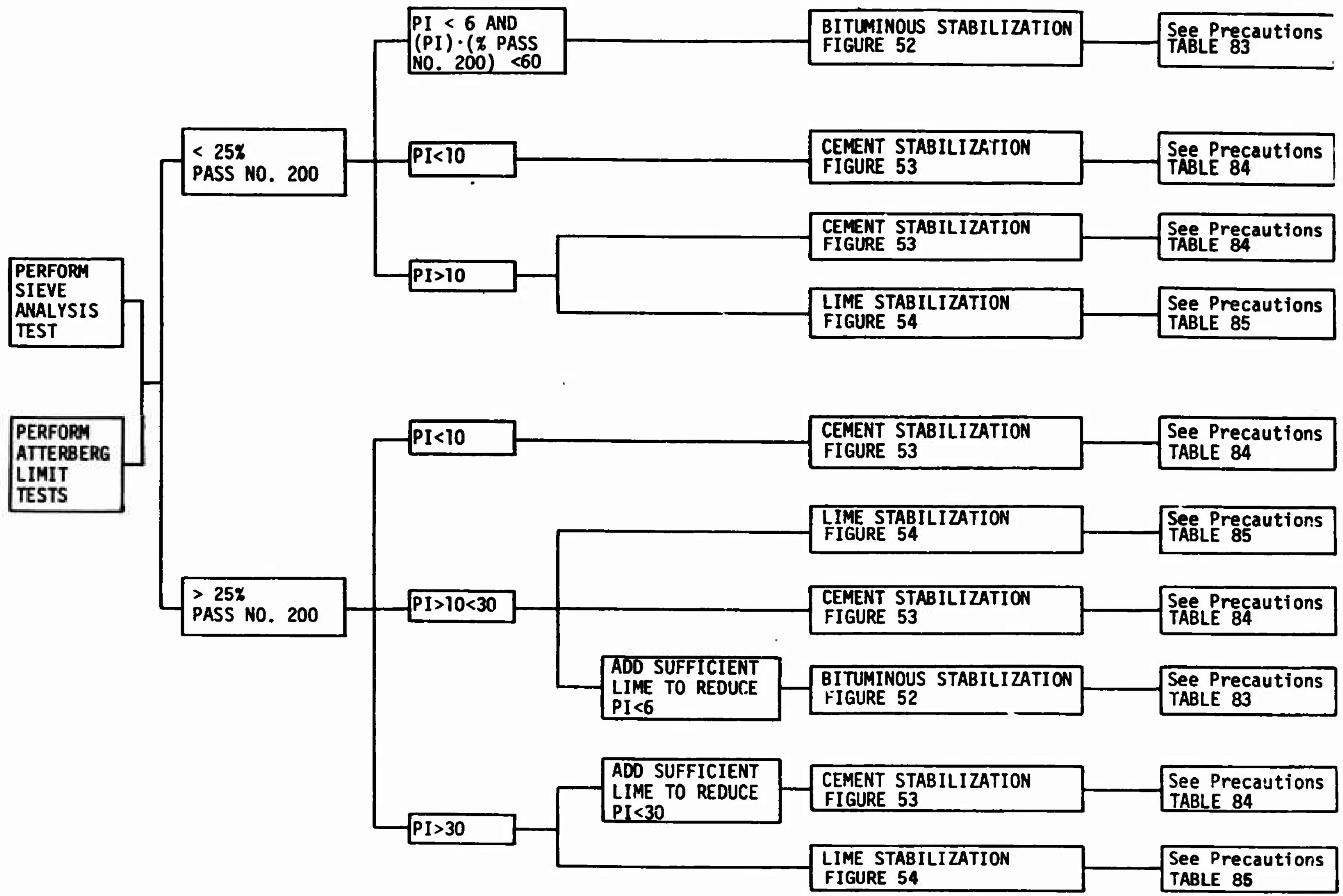


FIGURE 52. SELECTION OF STABILIZER FOR NONEXPEDIENT BASE CONSTRUCTION

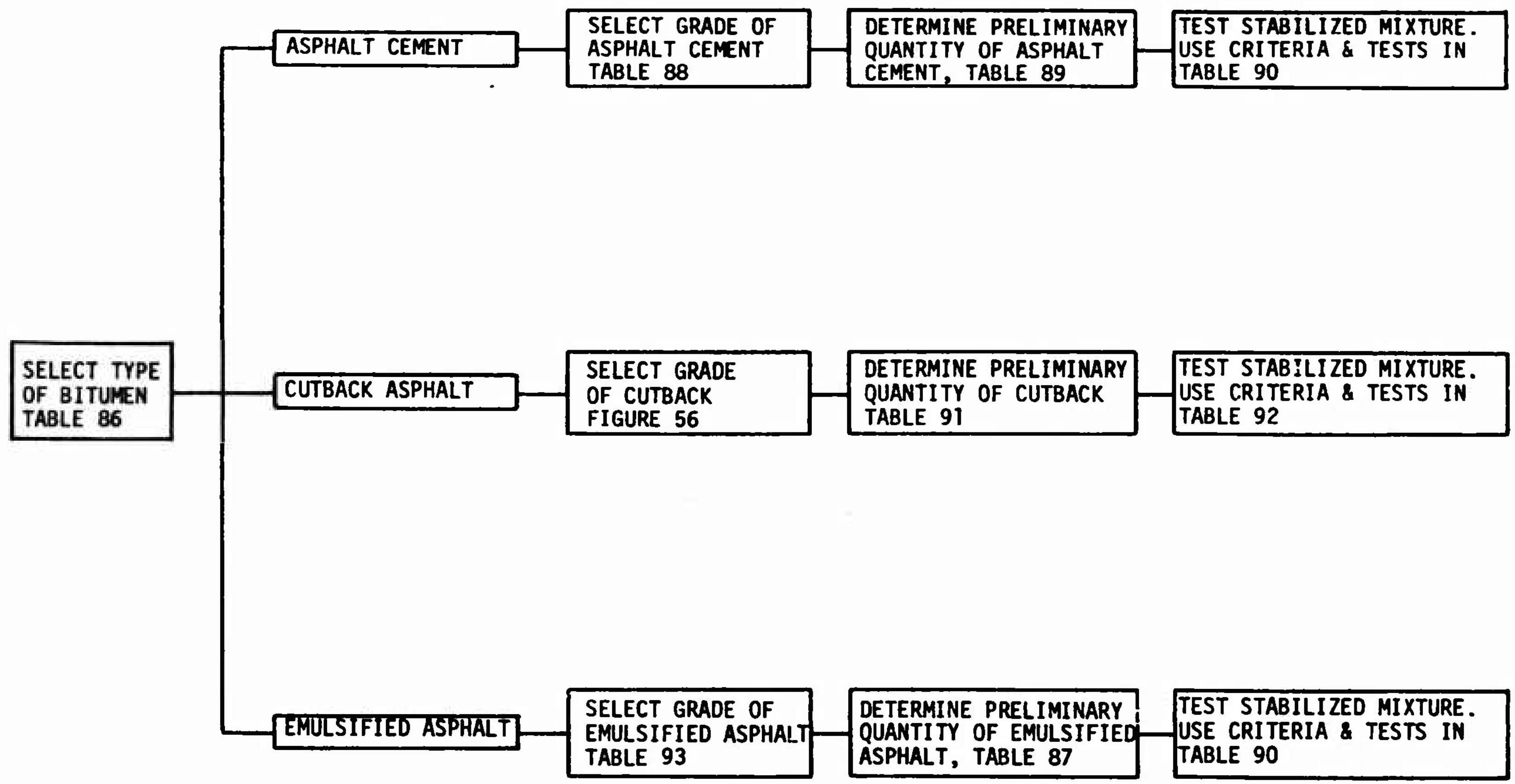


FIGURE 53. SUBSYSTEM FOR NON-EXPEDIENT BASE COURSE STABILIZATION WITH BITUMINOUS MATERIALS

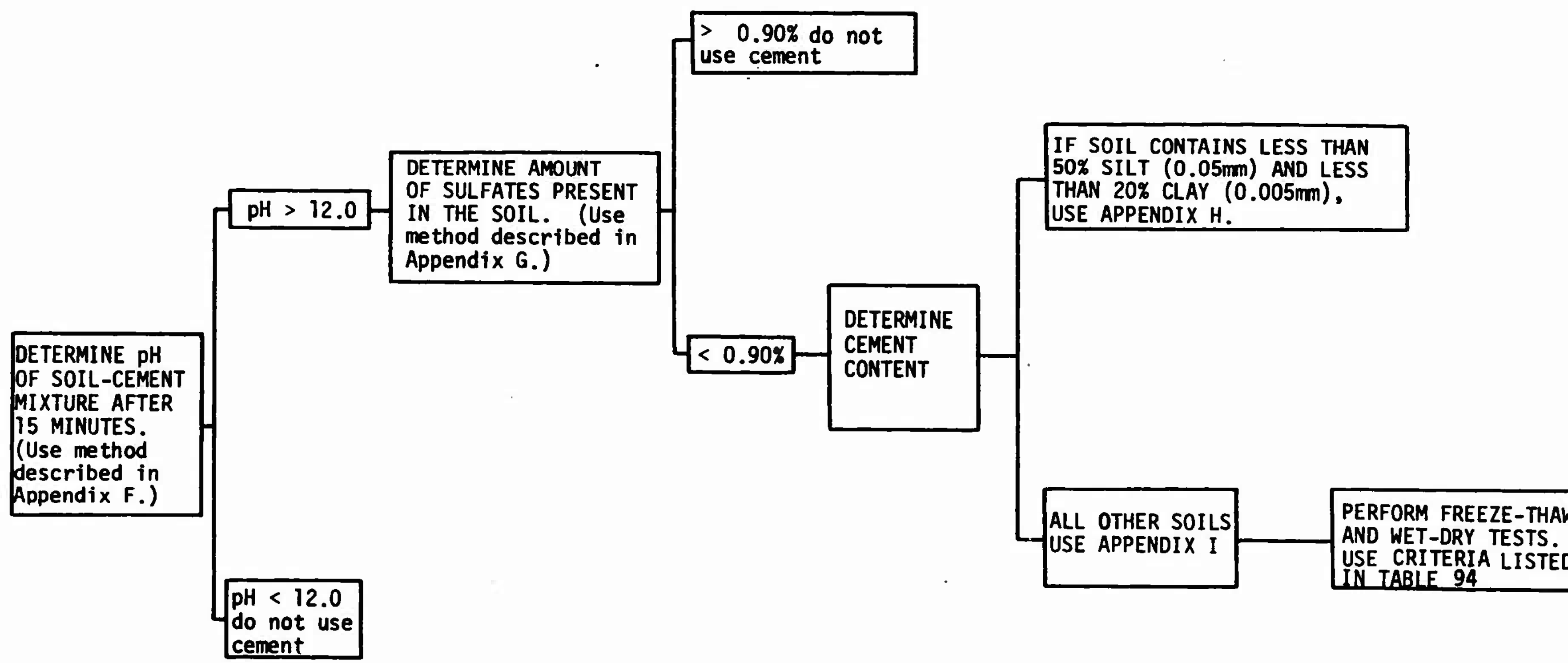


FIGURE 54. SUBSYSTEM FOR NON-EXPEDIENT BASE COURSE STABILIZATION WITH CEMENT

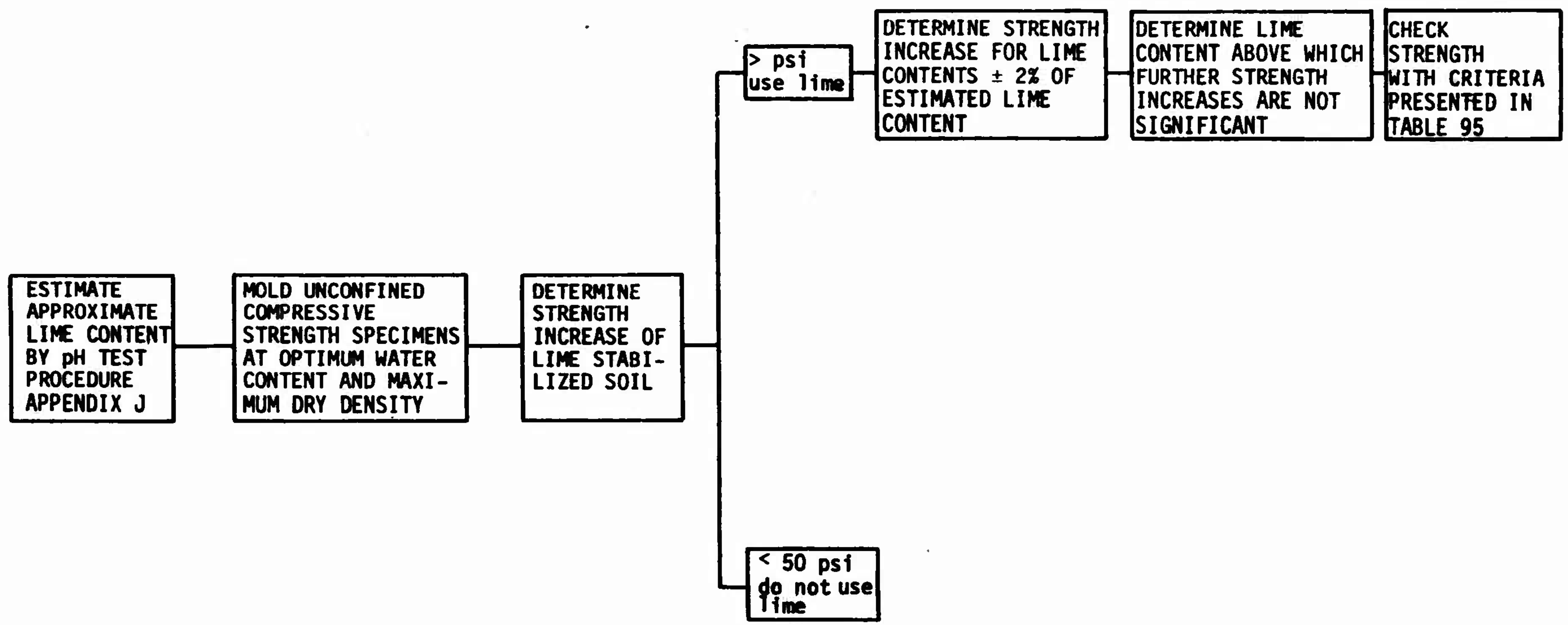
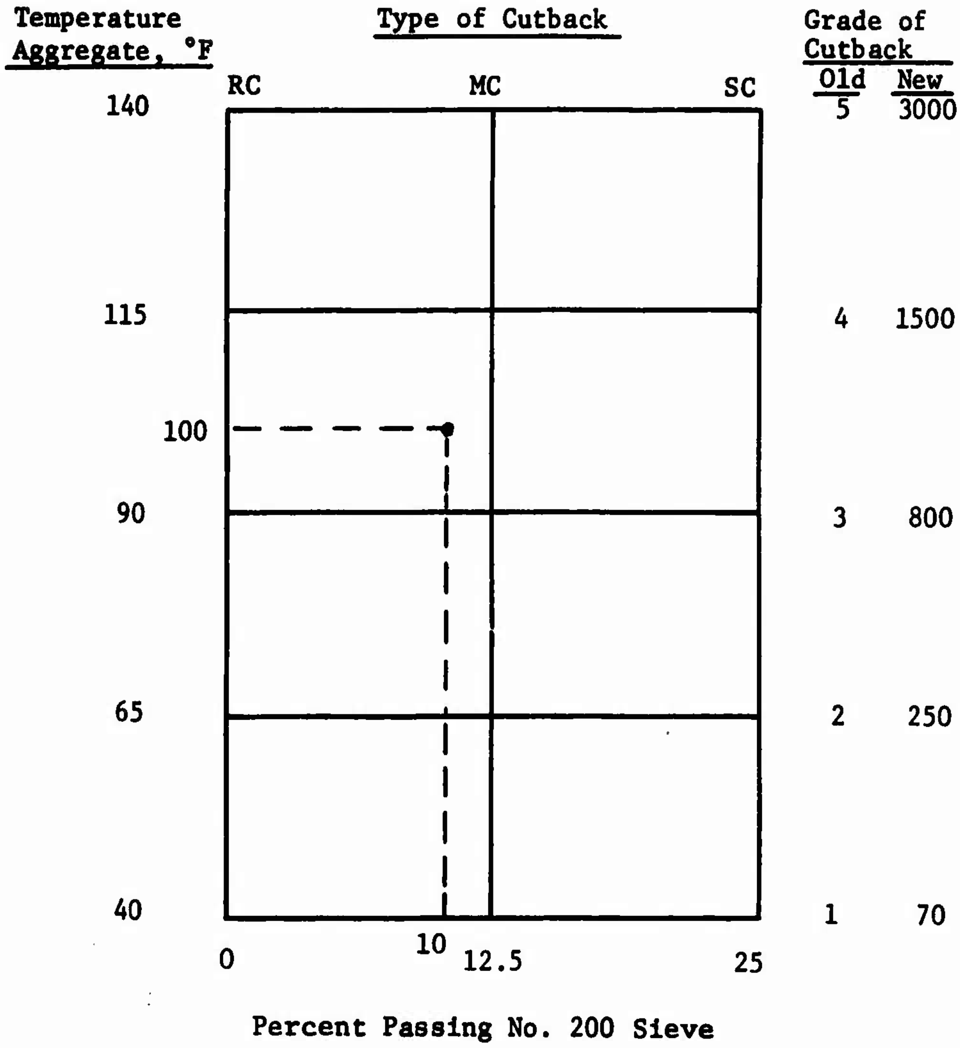


FIGURE 55. SUBSYSTEM FOR NON-EXPEDIENT BASE COURSE STABILIZATION WITH LIME



Example: For aggregate temperature of 100°F and 10% passing #200 sieve, use MC 800 cutback.

FIGURE 56. Selection of type of cutback for stabilization [after U. S. Navy (22)]

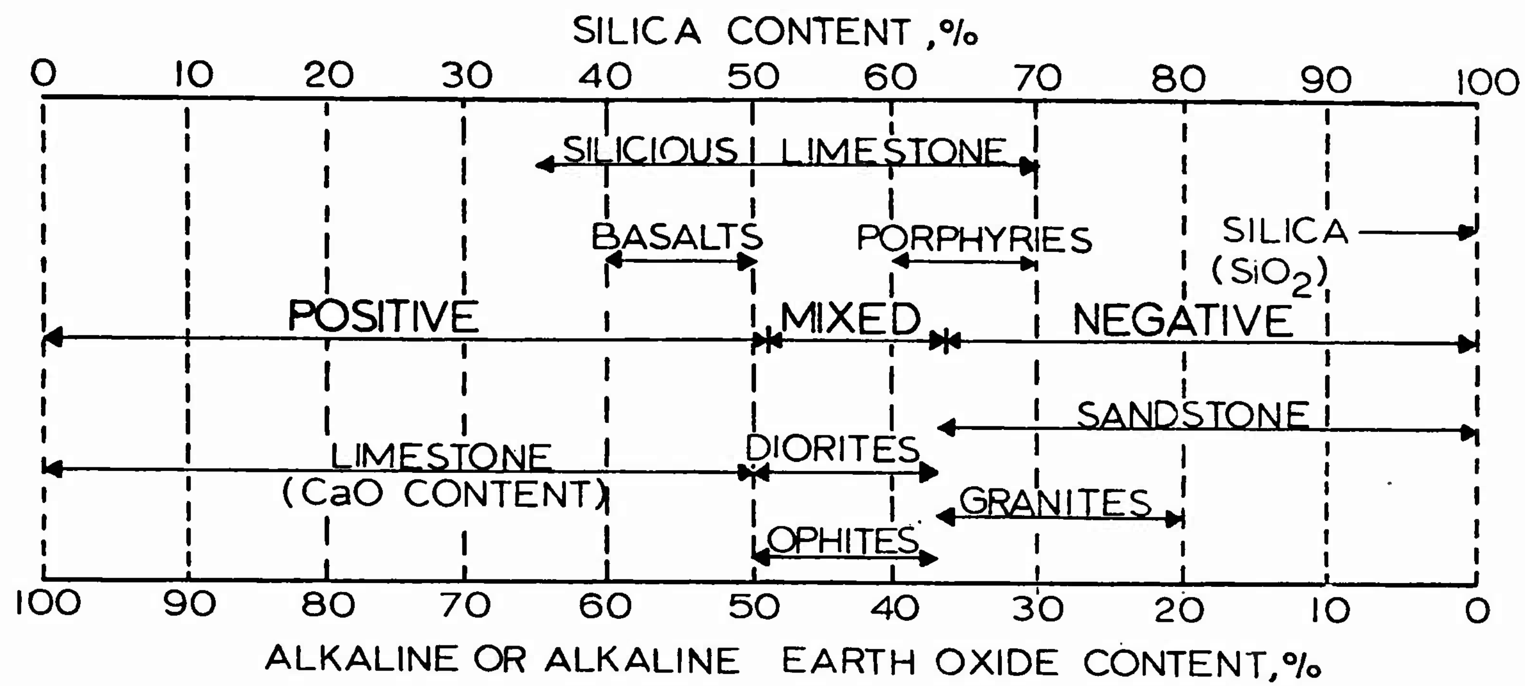


FIGURE 57. Classification of aggregates

[after Mertens and Wright (31)]

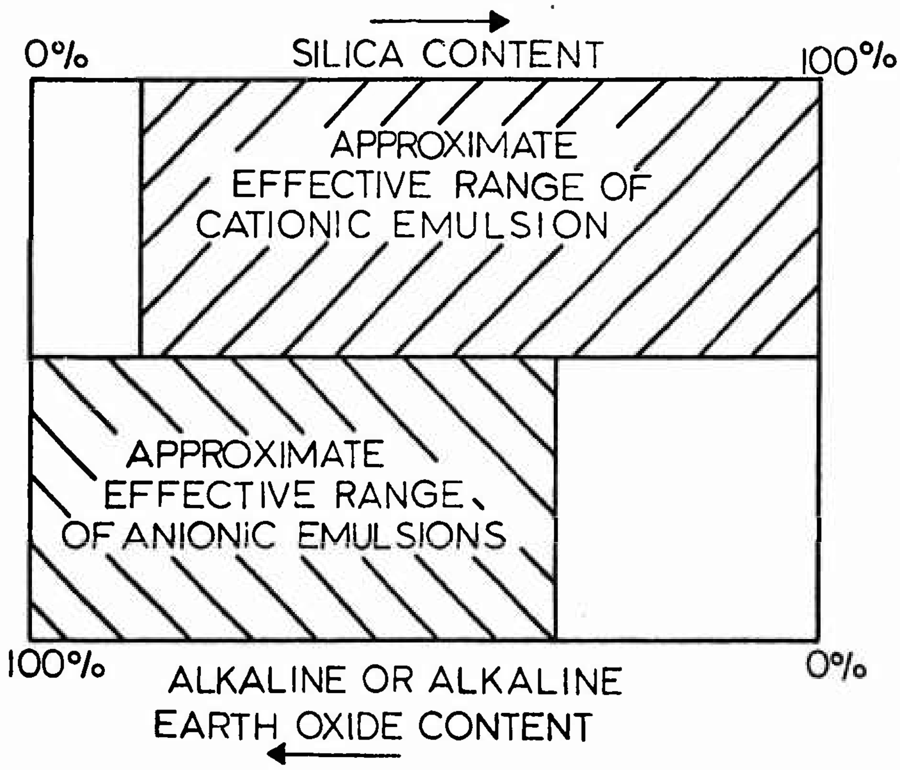


FIGURE 58. Approximate effective range of cationic and anionic emulsions on various types of aggregates

[after Mertens and Wright (31)]

TABLE 83

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR BITUMINOUS STABILIZATION IN NONEXPEDIENT BASE COURSES

Condition	Precautions
Environmental	When asphalt cements are used for bituminous stabilization, proper compaction must be obtained. If thin lifts of asphalt concrete are being placed, the air temperature should be 40°F and rising, and compaction equipment should be used immediately after lay down operation. Adequate compaction can be obtained at freezing temperatures if thick lifts are utilized. When cutbacks and emulsions are utilized, the air temperature and soil temperature should be above freezing. Bituminous materials should completely coat the soil particles before rainfall stops construction.
Construction	Central batch plants, together with other specialized equipment, are necessary for bituminous stabilization with asphalt cements. Hot dry weather is preferred for all types of bituminous stabilization.

TABLE 84

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR CEMENT STABILIZATION IN NONEXPEDIENT BASE COURSES

Condition	Precautions
Environmental	If the soil temperature is less than 60 to 70°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and strength gain of the cement-soil mixture will be minimal. If these environmental conditions are expected the cement may be expected to act as a soil modifier. Cement-soil mixtures should be scheduled for construction such that sufficient durability will be gained to resist any freeze-thaw cycles expected.
Construction	If heavy vehicles are allowed on the cement stabilized soils prior to a 10 to 14 day curing period, certain pavement damage can be expected.

TABLE 85

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

FOR LIME STABILIZATION IN NONEXPEDIENT BASE COURSES

Condition	Precautions
Environmental	If the soil temperature is less than 60 to 70°F and is not expected to increase for one month, chemical reactions will not occur rapidly, and the strength gain of the lime-soil mixture will be minimal. If these environmental conditions are expected the lime may be expected to act as a soil modifier. Lime-soil mixtures should be scheduled for construction such that sufficient durability will be gained to resist any freeze-thaw cycles expected.
Construction	If heavy vehicles are allowed on the lime stabilized soils prior to 10 to 14 day curing period, certain pavement damage can be expected.

TABLE 86

SELECTION OF A SUITABLE TYPE OF BITUMEN

FOR SOIL STABILIZATION PURPOSES

Sand Bitumen	Soil Bitumen	Crushed Stones and Sand-Gravel Bitumen
Hot Mix: Asphalt Cements 60-70 hot climate 85-100 120-150 cold climate		Hot Mix: Asphalt Cements 40-50 hot climate 60-70 85-100 cold climate
Cold Mix: Cutbacks See Figure 56	Cold Mix: Cutbacks See Figure 56	Cold Mix: Cutbacks See Figure 56
Emulsions See Table 93 See Figures 57 and 58 to determine if a catonic or anonic emulsion should be used	Emulsions See Table 93 See Figures 57 and 58 to determine if a catonic or anonic emulsion should be used	Emulsions See Table 93 See Figures 57 and 58 to determine if a catonic or anonic emulsion should be used

TABLE 87

EMULSIFIED ASPHALT REQUIREMENT

Percent passing No. 200	Lbs. of emulsified asphalt per 100 lbs. of dry aggregate when percent passing No. 10 sieve is:					
	50*	60	70	80	90	100
0	6.0	6.3	6.5	6.7	7.0	7.2
2	6.3	6.5	6.7	7.0	7.2	7.5
4	6.5	6.7	7.0	7.2	7.5	7.7
6	6.7	7.0	7.2	7.5	7.7	7.9
8	7.0	7.2	7.5	7.7	7.9	8.2
10	7.2	7.5	7.7	7.9	8.2	8.4
12	7.5	7.7	7.9	8.2	8.4	8.6
14	7.2	7.5	7.7	7.9	8.2	8.4
16	7.0	7.2	7.5	7.7	7.9	8.2
18	6.7	7.0	7.2	7.5	7.7	7.9
20	6.5	6.7	7.0	7.2	7.5	7.7
22	6.3	6.5	6.7	7.0	7.2	7.5
24	6.0	6.3	6.5	6.7	7.0	7.2
25	6.2	6.4	6.6	6.9	7.1	7.3

*50 or less.

[after U. S. Navy (22)]

TABLE 88

DETERMINATION OF ASPHALT GRADE FOR

BASE COURSE STABILIZATION

Pavement Temperature Index*	Asphalt Grade, Penetration
Negative	100-120
0-40	85-100
40-100	60-70
Above 100	40-50

*The sum, for a 1 - year period, of the increments above 75°F of monthly averages of the daily maximum temperatures. Average daily maximum temperatures for the period of record should be used where 10 or more years of record are available. For records of less than 10-year duration the record for the hottest year should be used. A negative index results when no monthly average exceeds 75°F. Negative indexes are evaluated merely by subtracting the largest monthly average from 75°F.

TABLE 89

SELECTION OF ASPHALT CEMENT CONTENT

FOR EXPEDIENT BASE COURSE CONSTRUCTION

Aggregate Shape and Surface Texture	Percent Asphalt by Weight of Dry Aggregate*
Rounded and Smooth	4
Angular and Rough	6
Intermediate	5

*Approximate quantities which may be adjusted in field based on observation of mix and engineering judgment.

TABLE 90

MIXTURE DESIGN CRITERIA

Marshall Criteria

Traffic Category	Heavy		Medium		Light	
Test Property	Min.	Max.	Min.	Max.	Min.	Max.
No. of Compaction Blows Each End of Specimen	75		50		35	
Stability, all mixtures	750	---	500	---	500	---
Flow, all mixtures	8	16	8	18	8	20
Percent Air Voids						
Surfacing or Leveling	3	5	3	5	3	5
Base	3	8	3	8	3	8
Percent Voids in Mineral Aggregate						

[after The Asphalt Institute (36)]

TABLE 91

DETERMINATION OF QUANTITY OF CUTBACK ASPHALT

$$p = 0.02\ (a) + 0.07\ (b) + 0.15\ (c) + 0.20\ (d)$$

where: p = percent of residual asphalt by weight of dry aggregate.

a = percent of mineral aggregate retained on No. 50 sieve.

b = percent of mineral aggregate passing No. 50 and retained on No. 100 sieve.

c = percent of mineral aggregate passing No. 100 and retained on No. 200 sieve.

d = percent of mineral aggregate passing No. 200 sieve.

TABLE 92

MARSHALL MIX DESIGN CRITERIA FOR

CUTBACK AND EMULSIFIED ASPHALT MIXTURES

Marshall Test	Criteria for a Test Temperature of 77°F	
	Minimum	Maximum
Stability, lbs.	750	---
Flow, (0.01 in.)	7	16
Percent air voids	3	5

[after Lefebvre (49)]

TABLE 93

SELECTION OF TYPE OF EMULSIFIED ASPHALT FOR STABILIZATION

Percent Passing # 200 Sieve	Relative Water Content of Soil	
	Wet (5%+)	Dry (0-5%)
0-5	SS-1h (or SS-Kh)	SM-K (or SS-1h*)
5-15	SS-1, SS-1h (or SS-K, SS-Kh)	SM-K (or SS-1h*, SS-1*)
15-25	SS-1 (or SS-K)	SM-K

*Soil should be pre-wetted with water before using these types of emulsified asphalts.

[after U. S. Navy (22)]

TABLE 94

PORTLAND CEMENT ASSOCIATION CRITERIA FOR

SOIL-CEMENT MIXTURES USED IN BASE COURSES

Soil Classification		Soil-Cement Weight Loss During 12 Cycles of Either Wet-Dry Test or Freeze-Thaw Test
AASHO	Unified*	
A-1	GW, GP, GM SW, SP, SM	less than or equal to 14 percent
A-2-4, A-2-5	GM, GC, SM, SC	
A-3	SP	
A-2-6, A-2-7	GM, GC, SM, SC	less than or equal to 10 percent
A-4	CL, ML	
A-5	ML, MH, OH	
A-6	CL, CH	less than or equal to 7 percent
A-7	OH, MH, CH	

*based on correlation presented by Air Force (2)

[after Portland Cement Association (10)]

TABLE 95

TENTATIVE LIME-SOIL MIXTURE COMPRESSIVE STRENGTH REQUIREMENTS

Anticipated Use	Residual Strength Requirement, psi (a)	Strength Requirements for Various Anticipated Service Conditions (b)			
		Extended (8 day) Soaking (psi)	Cyclic Freeze-Thaw (e) 3 Cycles (psi)	7 Cycles (psi)	10 Cycles (psi)
Modified Subgrade	20	50	50	90 50*	120
Subbase					
Rigid Pavement	20	50	50	90 50*	120
Flexible Pavement					
Thickness of Cover (c)					
10 inches	30	50	60	100 60*	130
8 inches	40	70	70	110 75*	140
5 inches	60	90	90	130 100*	160
Base	100(d)	130	130	170 150*	200

a) Minimum anticipated strength following first winter exposure.

b) Strength required at termination of field curing (following construction) to provide adequate residual strength.

c) Total pavement thickness overlying the subbase. The requirements are based on the Boussinesq stress distribution. Rigid pavement requirements apply if cemented materials are used as base courses.

d) Flexural strength should be considered in thickness design.

e) Number of freeze-thaw cycles expected in the lime-soil layer during the first winter of service.

*Note: Freeze-thaw strength losses based on 10 psi/cycle except for 7 cycle values indicated by an * which were based on a previously established regression equation.

[after Thompson (92)]

APPENDIX E

RAPID TEST PROCEDURES FOR EXPEDIENT CONSTRUCTION OPERATIONS USING SOIL-CEMENT STABILIZATION

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RAPID TEST PROCEDURES FOR EXPEDIENT CONSTRUCTION

OPERATIONS USING SOIL-CEMENT STABILIZATION*

A RAPID method of testing soil-cement has been used successfully for emergency construction and for very small projects where more complete testing is not feasible or practical. The engineer applying this procedure should be familiar with the details of the ASTM-AASHO soil-cement test methods described in Chapter 3 so that he can properly interpret and evaluate the data obtained with this rapid method.

The following steps, which are described in more detail in the following paragraphs, are suggested:

1. Determine the maximum density and optimum moisture content for the soil-cement mixture
2. Mold specimens for inspection of hardness.
3. Inspect specimens using "pick" and "click" procedures.

Moisture-Density Test

The maximum density and optimum moisture content are determined at 12 per cent cement by weight by means of the modified moisture-density test procedure described in Chapter 3.

In instances where the standard mold and rammer are not available, tests can be made by using a 2-in. diameter filled-in gas pipe of sufficient length to weigh 5.5 lb. as the compacting rammer and a No. 2½ tin can as the mold.

With experience the optimum moisture can be determined quite closely by "feel." When squeezed, soil-cement at optimum moisture will form a cast that will stick together when it is handled.

Molding Specimens

Specimens for inspection of hardness are molded by the same procedure described in Chapter 3. These specimens generally contain 10, 14 and 18 per cent cement by weight. It is best if these specimens can be molded in the standard mold, and then removed from the mold and placed in high humidity for hydration.

However, if a standard mold is not available it is possible to mold these specimens in No. 2½ tin cans, using the compacting rammer suggested above. The tin-can mold can be torn or ripped from the hardened soil-cement specimens with pliers after a few days.

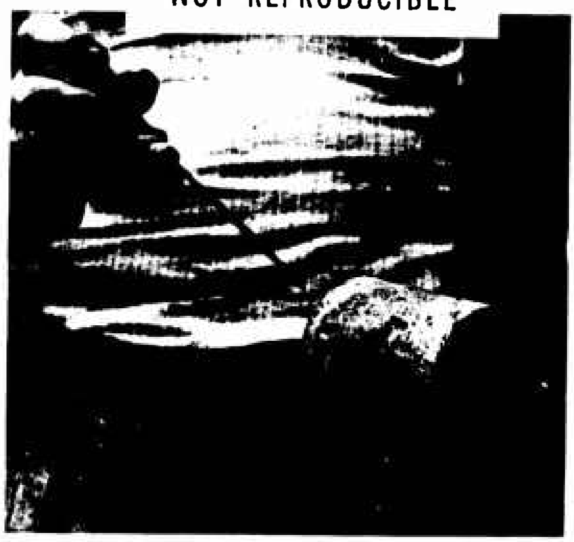
Inspecting Specimens

After at least a day or two of hardening, during which they are kept moist, and after a 3-hour soaking, the specimens are inspected by "picking" with a sharp-pointed instrument and by sharply "clicking" each specimen against a hard object such as concrete to determine their relative hardness when wet.

"Pick" Test

In the pick test, the specimen is held in one hand and a relatively sharp-pointed instrument, such as a dull ice pick, is lightly jabbed into the specimen (or the end of a specimen molded in a can) from a distance of two or three inches. If the specimen resists this light picking, the force of impact is increased until the pick is striking the specimen with considerable force. Specimens that are hardening satisfactorily will definitely resist the penetration of the pick,

NOT REPRODUCIBLE



The "pick" test.

*Since this material has been taken directly from the Portland Cement Association text, figure numbers and certain other references in this Appendix may not be in agreement with other portions of this report.

whereas specimens that are not hardening properly will resist little. To pass the pick test, a specimen that is not over 7 days old and that has been soaked in water must prevent the penetration of the ice pick, which is under considerable force, to a distance greater than about one-eighth to one-quarter inch.

"Click" Test

The click test is then applied to water-soaked specimens that are apparently hardening satisfactorily and that have passed the pick test. In the click test, the specimens are held perpendicular to each other and about four inches apart, one in each hand. They are then lightly clicked together a number of times, the force of impact being increased with each click. Specimens that are hardening satisfactorily will click together with a "ringing" or "solid" tone. As the force of impact is increased, one of the specimens may break transversely even though it is hardening adequately. The internal portion of a satisfactory specimen should then pass the pick test. When two or three hard specimens are once obtained they may be saved and one may be used in the click test with a soil-cement specimen of a soil in the process of being tested.

When a poorly hardened specimen is clicked with a satisfactory specimen, a "dull thud" sound is obtained rather than the "solid" sound obtained with two satisfactory specimens. After the first or second click the inferior specimen will generally break and its internal portion will not pass the pick test.

The "click" test.

At the time the click test is made, the age of the specimens must be taken into account. For instance, specimens that are not properly hardened at an age of 4 days may be satisfactorily hardened at an age of 7 days.

The above pick and click procedures are then repeated after the specimens have been dried out and again after a second soaking in order to test their relative hardness at both extremes of moisture content.

If equipment is available for making compression tests, these tests will provide further valuable data for study. It is suggested that duplicate specimens be molded and tested in compression at the age of 7 days and after a soaking in water for 4 hours. A satisfactory soil-cement mixture will have a compressive strength of about 400 lb. per sq.in. or more.

General Remarks

There is a distinct difference between satisfactorily hardened soil-cement specimens and inadequately hardened specimens. Even an inexperienced tester will soon be able to differentiate between them and to select a safe cement content to harden the soil. It is important to remember that an excess of cement is not harmful but that a deficiency of cement will result in inferior soil-cement.

If the 10 and 14 per cent specimens are apparently hardening satisfactorily and compression-test data are favorable, the project can immediately be started using a cement content of 12 per cent by weight. If the quantities of cement available for construction are limited and if the 10 per cent cement specimens are hard and have good compressive strength, additional specimens should be molded at 8 per cent cement, be permitted to hydrate and then be tested in the same manner as the other specimens. If the 8 per cent cement specimens are satisfactorily hardened, the cement content being used in construction can be reduced to 10 per cent.

Should a 10 per cent specimen be comparatively soft at 4 days' hydration, while the 14 and 18 per cent specimens are hardening satisfactorily, construction should be started using 16 per cent cement by weight until additional data are obtained.

In some unusual instances, the 18 per cent cement specimen may not harden satisfactorily. The engineer then has two alternatives: (1) the effect of higher cement contents may be investigated to see whether 22 or 26 per cent cement will harden the soil; or (2) a borrow soil requiring a relatively low cement factor may be located and hauled to the runway or roadway to "cap" the poor soil. The latter procedure will generally be the more economical one.

APPENDIX F

pH TEST ON SOIL-CEMENT MIXTURES

pH TEST ON SOIL-CEMENT MIXTURES

Materials:

1. Portland cement to be used for soil stabilization

Apparatus:

1. pH meter (the pH meter must be equipped with an electrode having a pH range of 14)
2. 150 ml. plastic bottles with screw-top lids
3. 50 m'. plastic beakers
4. Distilled water
5. Balance
6. Oven
7. Moisture cans

Procedure:

1. Standardize the pH meter with a buffer solution having a pH of 12.00.
2. Weigh to the nearest 0.01 gms., representative samples of air-dried soil, passing the No. 40 sieve and equal to 25.0 gms. of oven-dried soil.
3. Pour the soil samples into 150 ml. plastic bottles with screw-top lids.
4. Add 2.5 gms. of the portland cement.
5. Thoroughly mix soil and portland cement.

6. Add sufficient distilled water to make a thick paste. (Caution: too much water will reduce the pH and produce an incorrect result.)
7. Stir the soil-cement and water until thorough blending is achieved.
8. After 15 minutes, transfer part of the paste to a plastic beaker and measure the pH.
9. If the pH is 12.0 or greater, the soil organic matter content should not interfere with the cement stabilizing mechanism. To determine the required percent of cement, refer to design methods outlined in Figure 23 or 24, as appropriate.

APPENDIX G

DETERMINATION OF SULFATE IN SOILS

DETERMINATION OF SULFATE IN SOILS

GRAVIMETRIC METHOD

Scope

Applicable to all soil types with the possible exception of soils containing certain organic compounds. This method should permit the detection of as little as 0.05% sulfate as SO_4.

Reagents

1. Barium chloride, 10% solution of $BaCl_2 \cdot 2H_2O$. (Add 1 ml. 2% HCl to each 100 ml. of solution to prevent formation of carbonate.)
2. Hydrochloric acid, 2% solution (0.55 N)
3. Magnesium chloride, 10% solution of $MgCl_2 \cdot 6H_2O$
4. Demineralized water
5. Silver nitrate, 0.1 N solution.

Apparatus

1. Beaker, 1000 ml.
2. Burner and ring stand
3. Filtering flask, 500 ml.
4. Buchner funnel, 9 cm.
5. Filter paper, Whatman no. 40, 9 cm.
6. Filter paper, Whatman no. 42, 9 cm.
7. Saran wrap
8. Crucible, ignition, or aluminum foil, heavy grade

9. Analytical balance

10. Aspirator or other vacuum source

Procedure

1. Select a representative sample of air-dried soil weighing approximately 10 gm. Weigh to the nearest 0.01 gm. (Note: When sulfate content is anticipated to be less than 0.1%, a sample weighing 20 gm. or more may be used.) (The moisture content of the air-dried soil must be known for later determination of dry weight of the soil.)

2. Boil for 1 1/2 hours in beaker with mixture of 300 ml. water and 15 ml. HCl.

3. Filter through Whatman no. 40 paper, wash with hot water, dilute combined filtrate and washings to 500 ml.

4. Take 100 ml. of this solution and add $MgCl_2$ solution until no more precipitate is formed.

5. Filter through Whatman no. 42 paper, wash with hot water, dilute combined filtrate and washings to 200 ml.

6. Heat 100 ml. of this solution to boiling and add $BaCl_2$ solution very slowly until no more precipitate is formed. Continue boiling for about 5 minutes and let stand overnight in warm place, covering beaker with Saran wrap.

7. Filter through Whatman no. 42 paper. Wash with hot water until free from chlorides (filtrate should show no precipitate when a drop of $AgNO_3$ solution is added).

8. Dry filter paper in crucible or on sheet of aluminum foil. Ignite paper. Weigh residue on analytical balance as $BaSO_4$.

Calculation

$$\%SO_4 = \frac{\text{Weight of residue}}{\text{Oven-dry weight of initial sample}} \times 411.6$$

where

$$\text{Oven-dry weight of initial sample} = \frac{\text{Air-dry weight of initial sample}}{1 + \frac{\text{Air-dry moisture content (\%)}}{100\%}}$$

Note

If precipitated from cold solution, barium sulfate is so finely dispersed that it cannot be retained when filtering by the above method. Precipitation from a warm, dilute solution will increase crystal size. Due to the absorption (occlusion) of soluble salts during the precipitation of $BaSO_4$ a small error is introduced. This error can be minimized by permitting the precipitate to digest in a warm, dilute solution for a number of hours. This allows the more soluble small crystals of $BaSO_4$ to dissolve and recrystallize on the larger crystals.

DETERMINATION OF SULFATE IN SOILS

TURBIDIMETRIC METHOD

Reagents:

1. Barium chloride crystals (Grind analytical reagent grade barium chloride to pass a 1 mm sieve)
2. Ammonium acetate solution (0.5N). (Add dilute hydrochloric acid until the solution has a pH of 4.2)
3. Distilled water

Apparatus:

1. Moisture can
2. Oven
3. 200 ml. beaker
4. Burner and ring stand
5. Filtering flask
6. Buchner funnel, 9 cm.
7. Filter paper, Whatman No. 40, 9 cm.
8. Vacuum source
9. Spectrophotometer and standard tubes (Bausch and Lomb Spectronic 20 or equivalent).
10. pH meter

Procedure:

1. Take a representative sample of air-dried soil weighing approximately 10 gms., and weigh to the nearest 0.01 gms. (The moisture content of the air-dried soil must be known for later determination of dry weight of the soil.)
2. Add the ammonium acetate solution to the soil. (The ratio of soil to solution should be approximately 1:5 by weight.)
3. Boil for about 5 minutes.
4. Filter through Whatman No. 40 filter paper. If the extracting solution is not clear, filter again.
5. Take 10 ml. of extracting solution (this may vary depending on the concentration of sulfate in the solution) and dilute with distilled water to about 40 ml. Add about 0.2 gm. of barium chloride crystals and dilute to make the volume exactly equal to 50 ml. Stir for 1 minute.
6. Immediately after the stirring period has ended, pour a portion of the solution into the standard tube and insert the tube into the cell of the spectrophotometer. Measure the turbidity at 30 sec. intervals for 4 minutes. Maximum turbidity is usually obtained within 2 minutes and the readings remain constant thereafter for 3-10 minutes. Consider the turbidity to be the maximum reading obtained in the 4 minute interval.
7. Compare the turbidity reading with a standard curve and compute the sulfate concentration (as SO_4) in the original extracting solution. (The standard curve is secured by carrying out the procedure with standard potassium sulfate solutions.)
8. Correction should be made for the apparent turbidity of the samples by running blanks in which no barium chloride is added.

Sample Calculation:

Given: Wt. of air-dried sample = 10.12 gms.

Water Content = 9.36%

Wt. of dry soil = 9.27 gms.

Total volume of extracting solution = 39.1 ml.

10 ml. of extracting solution was diluted to 50 ml. after addition of barium chloride (see step 5). The solution gave a transmission reading of 81.

Calculation:

From the standard curve, a transmission reading of 81 corresponds to 16.0 ppm. (see following figure).

$\therefore$ Concentration of original extracting solution = 16.0 x 5 = 80.0 ppm.

$$\%\ SO_4^{--} = \frac{80.0 \times 39.1 \times 100}{1000 \times 1000 \times 9.27} = 0.0338\%$$

Determination of Standard Curve:

1. Prepare sulfate solutions of 0, 4, 8, 12, 16, 20, 25, 30, 35, 40, 45, 50 ppm. in separate test tubes. The sulfate solution is made from potassium sulfate salt dissolved in 0.5 N ammonium acetate (with pH adjusted to 4.2).
2. Continue Steps 5 and 6 in the procedure as described in Determination of Sulfate in Soil by Turbidimetric Method.
3. Draw standard curve as shown in following figure by plotting transmission readings for known concentrations of sulfate solutions.

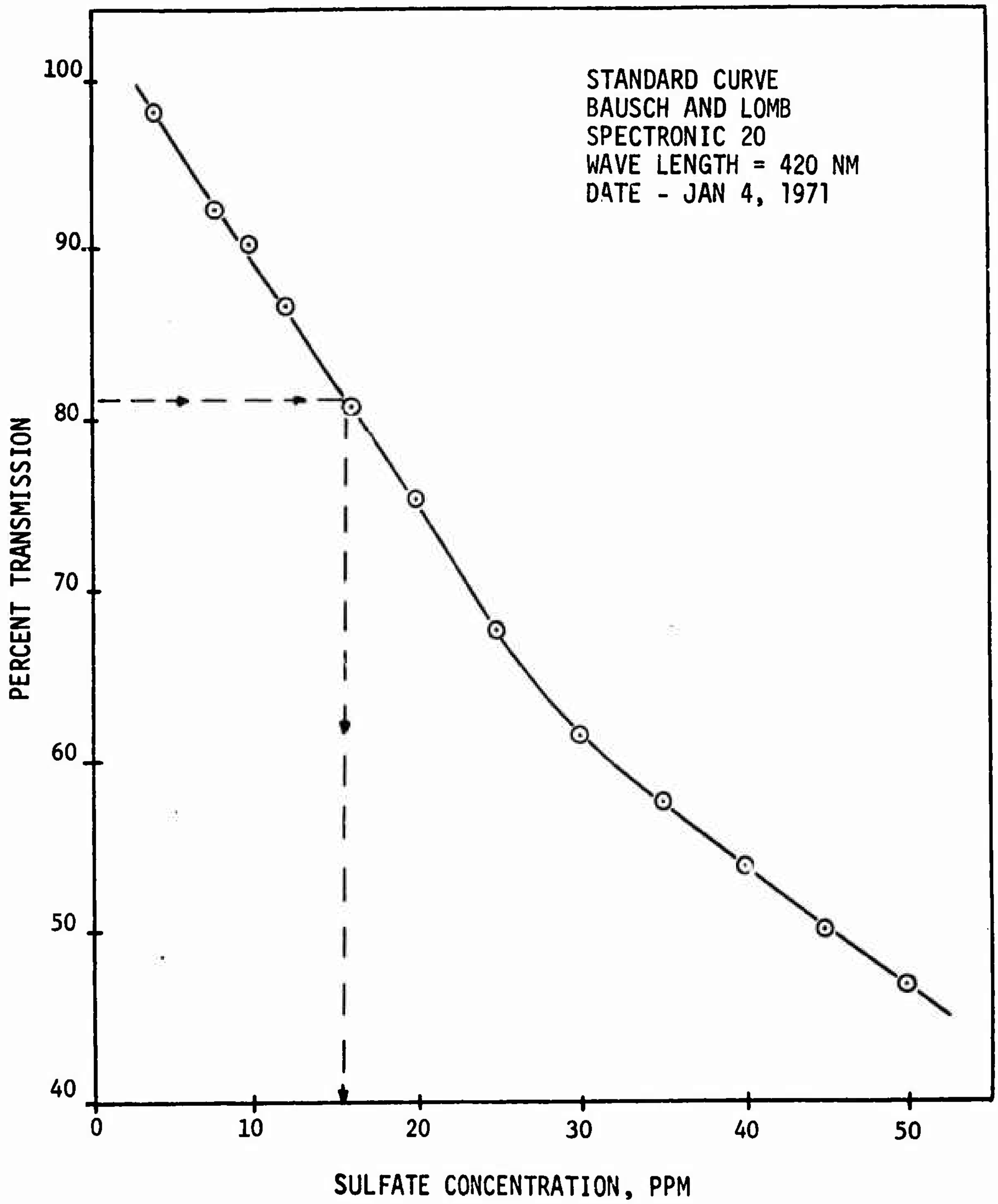


FIGURE 59. EXAMPLE STANDARD CURVE FOR SPECTROPHOTOMETER

APPENDIX H

SELECTION OF CEMENT CONTENT FOR CEMENT STABILIZED SANDY SOIL

SELECTION OF CEMENT CONTENT FOR CEMENT STABILIZED SANDY SOIL *

THE following short-cut test procedures for sandy soils were developed as a result of a correlation made by the Portland Cement Association of the data obtained from ASTM-AASHO tests on 2,438 sandy soils. These procedures do not involve new tests or additional equipment. Instead, some tests can be eliminated by the use of charts developed in previous tests on similar soils. The only tests required are a grain-size analysis, a moisture-density test and compressive-strength tests. Relatively small samples are needed. All tests, except for the 7-day compressive-strength tests, can be completed in one day.

Two procedures are used: Method A for soils not containing material retained on the No. 4 sieve and Method B for soils containing material retained on the No. 4 sieve. Method B was recently developed to permit the use of moisture-density data obtained on the total soil-cement mixture, as specified by the ASTM-AASHO moisture-density test methods revised in 1957.

The procedures can be used only with soils containing less than 50 per cent material smaller than 0.05 mm. (silt and clay) and less than 20 per cent material smaller than 0.005 mm. (clay). These were the gradation limits for the soils that were included in the correlation used to develop the original charts. Dark grey to black soils with appreciable amounts of organic impurities were not included in the correlation and therefore cannot be tested by these procedures. This is also true of miscellaneous granular materials such as cinders, caliche, chat, chert, marl, red dog, scoria, shale, slag, etc. Moreover, the short-cut procedures cannot be used with granular soils containing material retained on the No. 4 sieve if that material has a bulk specific gravity less than 2.45.

The short-cut test procedures do not always indicate the minimum cement factor that can be used with a particular sandy soil. However, they almost always provide a safe cement factor, generally close to that indicated by standard ASTM-AASHO wet-dry and freeze-thaw tests.

The procedures are being widely applied by engineers and builders and may largely replace the standard tests when experience in their use is gained and the relationships are checked. The charts and procedures may be modified to conform to local climatic and soil conditions if necessary.

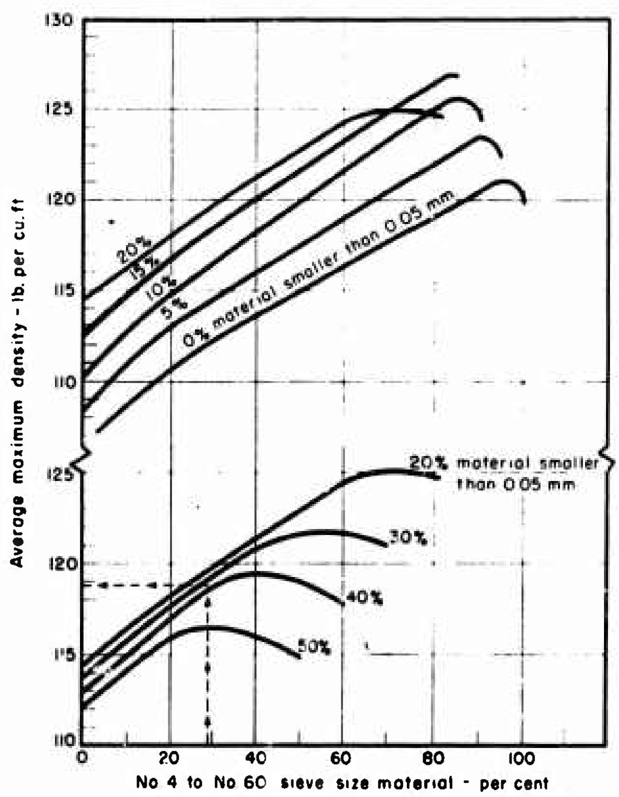


Fig. 35. Average maximum densities of soil-cement mixtures not containing material retained on the No. 4 sieve.

Step-by-Step Procedures

Short-cut test procedures involve:

1. Running a moisture-density test on a mixture of the soil and portland cement.
2. Determining the indicated portland cement requirement by the use of charts.
3. Verifying the indicated cement requirement by compressive-strength tests.

Preliminary Steps

Before applying the short-cut test procedures, it is nec-

*Since this material has been taken directly from the Portland Cement Association text, figure numbers and certain other references in this Appendix may not be in agreement with other portions of this report.

essary (1) to determine the gradation of the soil, and (2) to determine the bulk specific gravity of the material retained on the No. 4 sieve.* If all the soil passes the No. 4 sieve, Method A should be used. If material is retained on the No. 4 sieve, Method B is used.

Method A

Step 1: Determine by test the maximum density and optimum moisture content for a mixture of the soil and portland cement.**

Note 1: Use Fig. 35 to obtain an estimated maximum density of the soil-cement mixture being tested. This estimated maximum density and the percentage of material smaller than 0.05 mm. (No. 270 sieve) can be used with Fig. 36 to determine the cement content by weight to use for the test.

Step 2: Use the maximum density obtained by test in Step 1 to determine from Fig. 36 the indicated cement requirement.

Step 3: Use the indicated cement factor obtained in Step 2 to mold compressive-strength test specimens† in triplicate at maximum density and optimum moisture content.

Step 4: Determine the average compressive strength of the specimens after 7 days' moist-curing.

Step 5: On Fig. 37, plot the average compressive-strength value obtained in Step 4. If this value plots above the curve, the indicated cement factor by weight, determined in Step 2, is adequate.

For field construction, use Fig. 41 to convert this cement content by weight to a volume basis.

Note 2: If the average compressive-strength value plots below the curve of Fig. 37, the indicated cement factor obtained in Step 2 is probably too low. Additional tests will be needed to establish a cement requirement. These tests generally require the molding of two test specimens, one at the indicated cement factor obtained in Step 2 and one at a cement content two percentage points higher. The specimens are then tested by ASTM-AASHO freeze-thaw test procedures.

Method B

Step 1: Determine by test the maximum density and optimum moisture content for a mixture of the soil and portland cement.††

Note 3: Use Fig. 38 to determine an estimated maximum density of the soil-cement mixture being tested. This estimated maximum density, the percentage of material

*The short-cut tests do not apply to soils containing more than 50 per cent silt and clay smaller than 0.05 mm. and more than 20 per cent clay smaller than 0.005 mm., or to dark grey or black organic soils. These soils, as well as miscellaneous granular materials such as cinders, caliche, chat, chert, marl, red dog, scoria, shale, slag, etc., and soils containing material retained on the No. 4 sieve having a bulk specific gravity less than 2.45 should not be used but should be tested by the ASTM-AASHO procedures.

**Methods of Test for Moisture-Density Relations of Soil-Cement Mixtures, ASTM Designation D558-57; AASHO Designation T134-57.

†Specimens of either 2-in. diameter and 2-in. height or 4-in. diameter and 4.6-in. height may be molded. The 2-in. specimens shall be submerged in water for one hour before testing and the 4-in. specimens for four hours. The 4-in. specimens shall be capped before testing.

††Methods of Test for Moisture-Density Relations of Soil-Cement Mixtures, ASTM Designation D558-57; AASHO Designation T134-57.

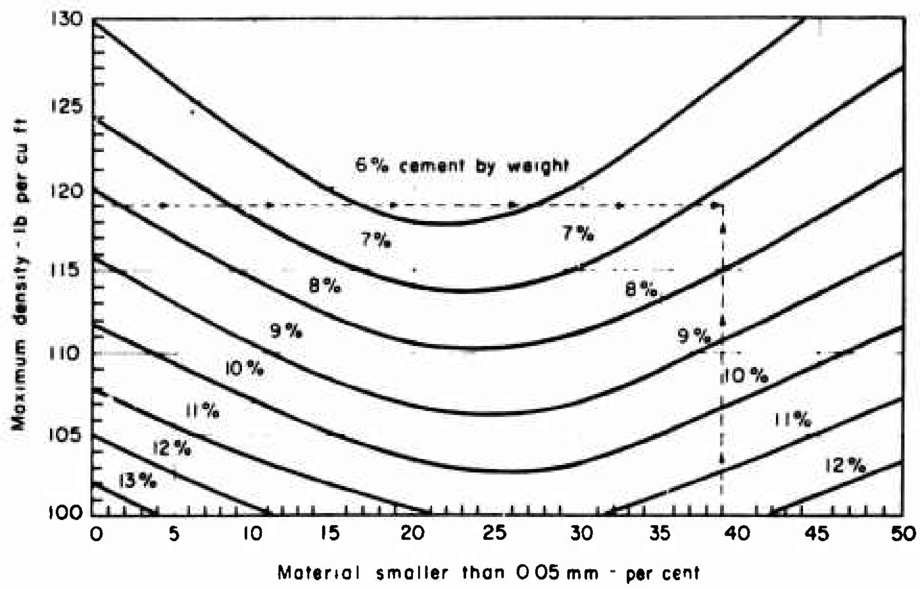


Fig. 36. Indicated cement contents of soil-cement mixtures not containing material retained on the No. 4 sieve.

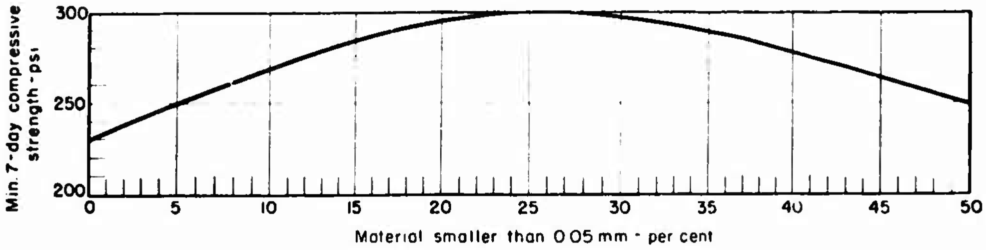


Fig. 37. Minimum 7-day compressive strengths required for soil-cement mixtures not containing material retained on the No. 4 sieve.

smaller than 0.05 mm. (No. 270 sieve), and the percentage of material retained on the No. 4 sieve can be used with Fig. 39 to determine the cement content by weight to use in the test.

The soil sample for the test shall contain the same percentage of material retained on the No. 4 sieve as the original soil sample contains, except that a maximum of 45 per cent is used. Also, ¾-in. material is the maximum size used. Should there be material larger than this in the original soil sample, it is replaced in the test sample with an equivalent weight of material passing the ¾-in. sieve and retained on the No. 4 sieve.

Step 2: Use the maximum density obtained by test in Step 1 to determine from Fig. 39 the indicated cement requirement.

Step 3: Use total material as described in Step 1 and the indicated cement factor obtained in Step 2 to mold compressive-strength test specimens* in triplicate at maximum density and optimum moisture content.

Step 4: Determine the average compressive strength of the specimens after 7 days' moist-curing.

Step 5: Determine from Fig. 40 the minimum allowable compressive strength for the soil-cement mixture. If the average compressive strength obtained in Step 4 equals or exceeds the minimum allowable strength, the indicated cement factor by weight obtained in Step 2 is adequate.

For field construction, use Fig. 41 to convert this cement content by weight to a volume basis.

Note 4: If the average compressive-strength value is lower than the minimum allowable, the indicated cement factor obtained in Step 2 is probably too low. Additional tests as described in Note 2 are needed.

Example of Use of Short-Cut Test Procedures

Following is an example of the use of the short-cut procedures.

*Specimens of 4-in. diameter and 4.6-in. height shall be molded. They shall be submerged in water for four hours and shall be capped before testing.

Preliminary tests determine the gradation of the soil and bulk specific gravity of the material, if any, retained on the No. 4 sieve. The data obtained from the tests are tabulated below. In this example, Method B should be used since the soil contains material retained on the No. 4 sieve.

Gradation:

Passing

No. 4 sieve	82 per cent
No. 10 sieve	77 per cent
No. 60 sieve	58 per cent
No. 200 sieve	37 per cent

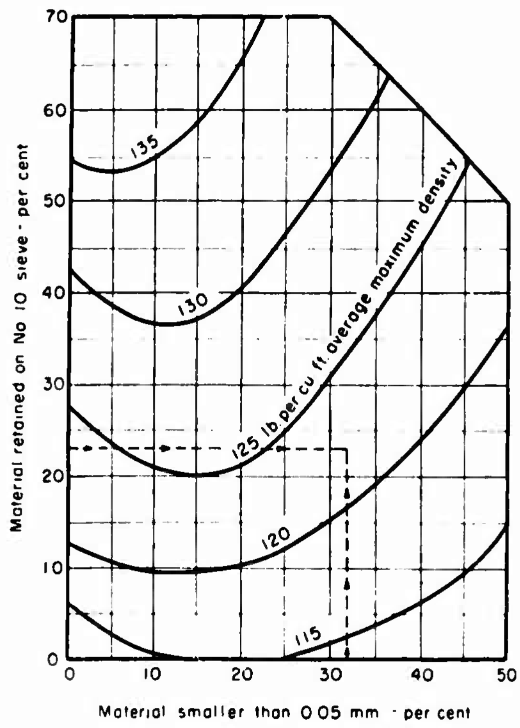


Fig. 38. Average maximum densities of soil-cement mixtures containing material retained on the No. 4 sieve.

Smaller than
 0.05 mm. (silt and clay
 combined) .... 32 per cent
 0.005 mm. (clay) .... 13 per cent

Color: Brown

Bulk specific gravity of material retained on No. 4 sieve: 2.50.

Step 1: Fig. 38 indicates that the estimated maximum density of the soil-cement mixture is 122 lb. per cu.ft. since the soil contains 32 per cent material smaller than 0.05 mm. and 23 per cent material retained on the No. 10 sieve.

Fig. 39 is used to determine the cement content by weight to use in the moisture-density test. Since the soil contains 32 per cent material smaller than 0.05 mm. and 18 per cent material retained on the No. 4 sieve, and since the estimated maximum density is 122 lb. per cu.ft., 6 per cent cement by weight is indicated.

Perform the moisture-density test.

For this example, assume the maximum density obtained by test to be 123.2 lb per cu.ft. at 10.2 per cent moisture.

Step 2: Fig. 39 indicates a cement factor of 6 per cent, using the calculated actual density of 123.2 lb. per cu.ft.

Step 3: Using total material and 6 per cent cement by weight, mold compressive-strength test specimens in triplicate at maximum density (123.2 lb. per cu.ft.) and optimum moisture (10.2 per cent).

Step 4: Determine the average 7-day compressive strength.

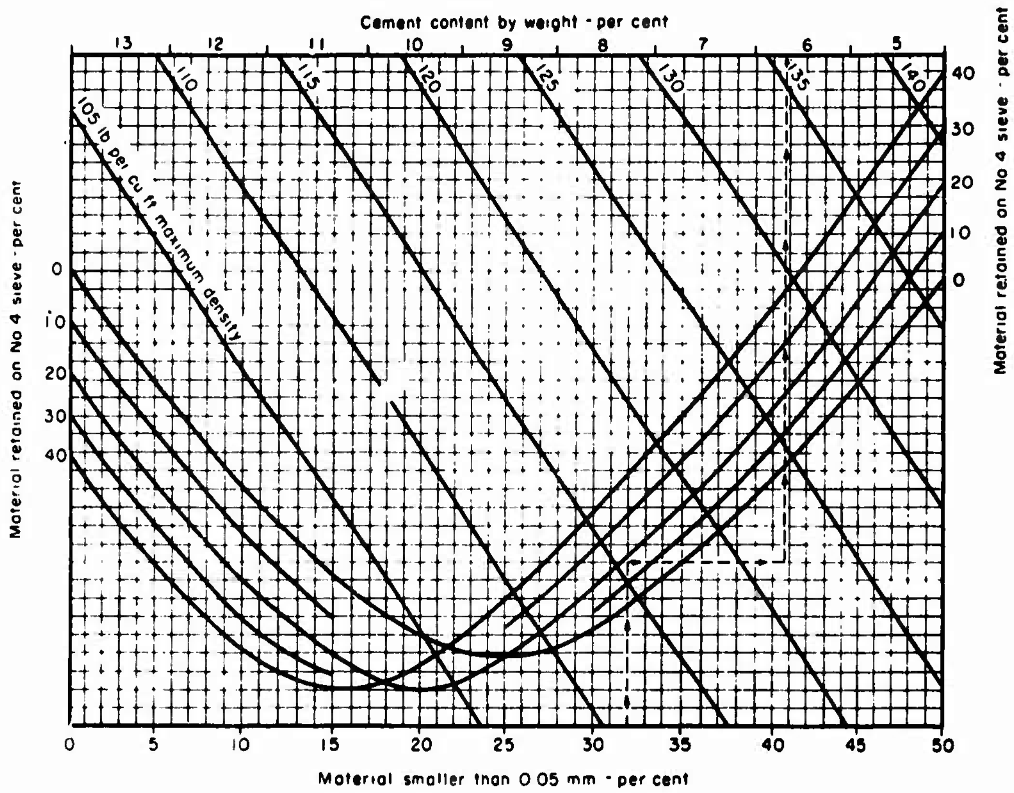
For this example, assume the average compressive strength to be 345 psi.

Step 5: Since the soil contains 32 per cent material smaller than 0.05 mm. and 18 per cent material retained on the No. 4 sieve, the minimum allowable compressive strength for this soil-cement mixture is 280 psi, as shown in Fig. 40. The average compressive strength of the mixture used in this example (345 psi), as obtained in Step 4, is higher than the minimum allowable strength. Therefore, the indicated cement content of 6 per cent by weight is adequate.

For field construction, Fig. 41 shows that 6 per cent cement by weight is equivalent to 7.4 per cent cement by volume.

If the average compressive strength in Step 4 had been

Fig. 39. Indicated cement contents of soil-cement mixtures containing material retained on the No. 4 sieve.



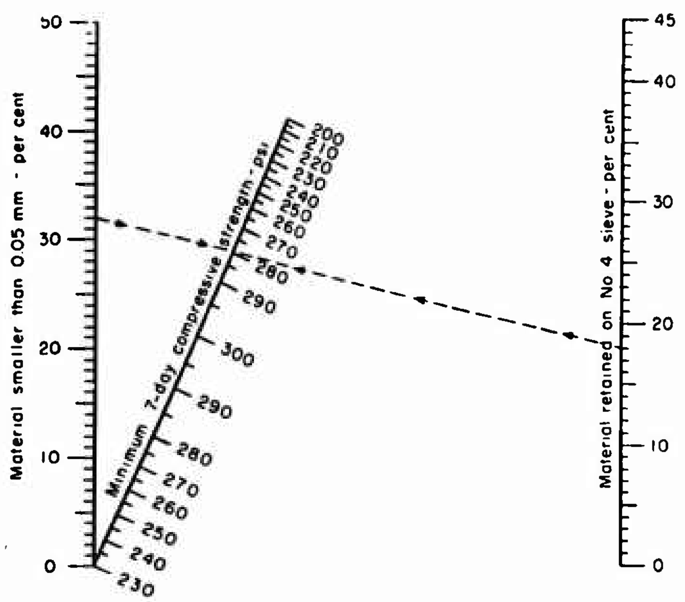


Fig. 40. Minimum 7-day compressive strengths required for soil-cement mixtures containing material retained on the No. 4 sieve.

lower than the minimum allowable strength, say 245 psi, 6 per cent cement by weight probably would not have been adequate. Additional testing would then have been required to establish the cement requirement for the soil.

These tests would involve molding and testing freeze-thaw test specimens according to ASTM-AASHO procedures. Freeze-thaw specimens containing 6 and 8 per cent cement by weight would probably be adequate in this instance.

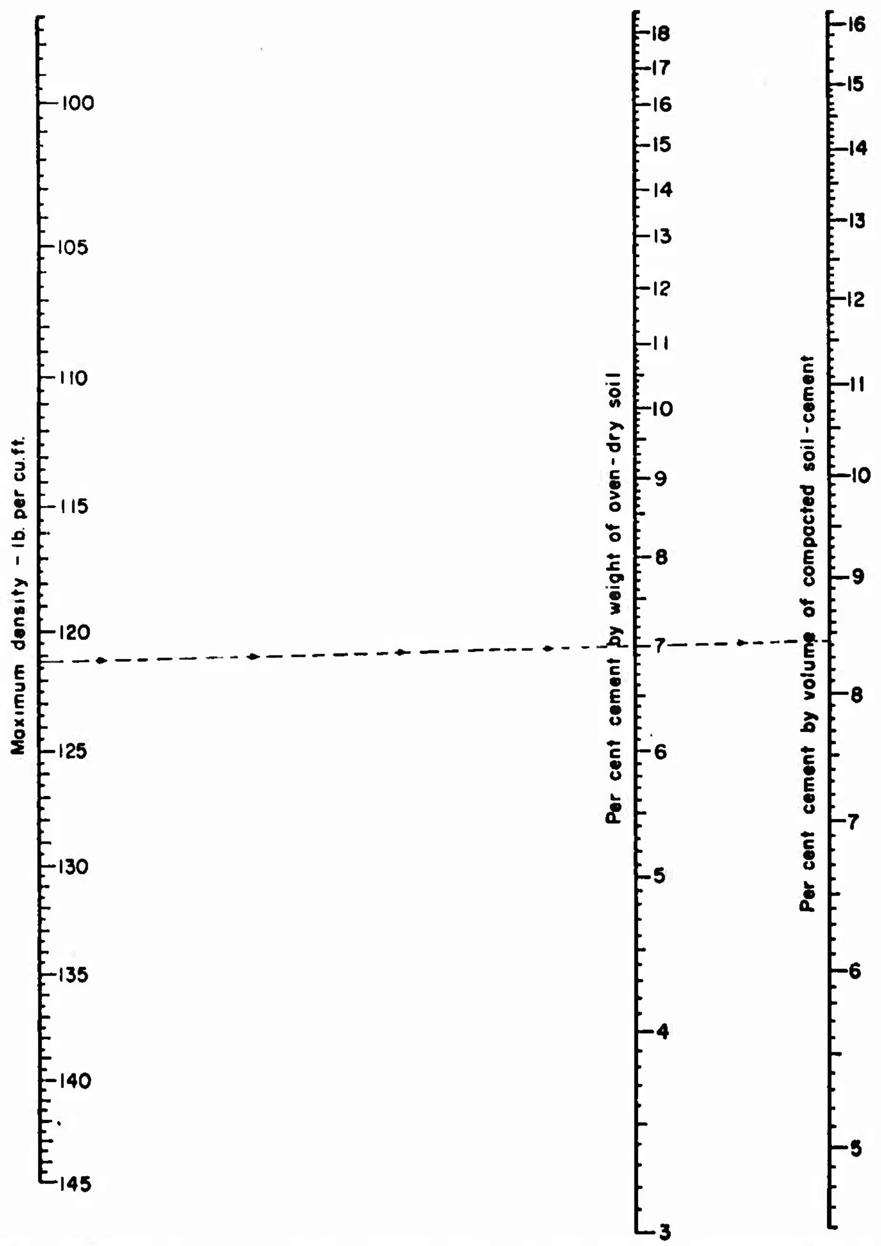


Fig. 41 Relation of cement content by weight of oven-dry soil to cement content by volume of compacted soil-cement mixture.

APPENDIX I

SELECTION OF CEMENT CONTENT FOR BASE
COURSE SOIL-CEMENT MIXTURES

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SELECTION OF CEMENT CONTENT FOR BASE COURSE SOIL-CEMENT MIXTURES*

THIS chapter will be of major interest to the laboratory engineer because it will assist him in determining what cement contents to investigate in the soil-cement tests. The field engineer and administrative engineer will also be interested because the properties of soil-cement mixtures and the relationships existing among these properties and various test values are discussed. Information is presented that will enable engineers to estimate probable cement factors so that job estimates can be made before any tests are made.

In order to obtain the maximum amount of information from the wet-dry and freeze-thaw tests, it is important that the laboratory engineer design the soil-cement specimens properly. For instance, if specimens are designed with very high cement contents, they will all pass the wet-dry and freeze-thaw tests; and a minimum cement factor will not have been determined. On the other hand, if the specimens are designed with inadequate cement contents, they will all fail in the tests.

The principal requirement of a hardened soil-cement mixture is that it withstand exposure to the elements. Strength might also be considered a principal requirement; however, since most soil-cement mixtures that possess adequate resistance to the elements also possess adequate strength, this requirement is secondary.

Therefore, in a study to determine when a certain soil-cement mixture has been adequately hardened, the requirement of adequate resistance to exposure is the first considered. That is, will the hardened soil-cement mixture withstand the wetting and drying and the freezing and thawing cycles of nature and still maintain at least the stability inherent in the mass at the time the roadway was opened to traffic?

For instance, consider a hypothetical road subgrade made from a clay loam soil without cement, packed to maximum density at a moisture content slightly less than its optimum moisture content. This mass can withstand relatively heavy loads without failure, although it cannot offer much resistance to abrasive forces.

The same soil mixed with cement and compacted to maximum density at optimum moisture content will have stability before the cement hydrates at least equal to that of the raw soil.

But consider the two cases at a later date under a condition of slow drainage when moisture, by capillary action or in some other manner, has permeated the masses. The voids in the raw soil become filled with water and the soil loses the original inherent physical stability that was built into it by compaction to maximum density. This is not so, however, with the adequately hardened soil-cement mixture, which has continually increased in stability since its construction because of cement hydration and resultant cementation. Its air voids will become filled with water too, but its stability will still be much greater than that built into it originally.

The next important requirement to consider is economy. Available data indicate that about 85 per cent of all soils likely to be used for soil-cement can be adequately hardened by the addition of 14 per cent cement or less. To determine whether or not a soil falls into this category would not require much testing. However, more than 50 per cent of all soils so far tested for soil-cement require only 10 per cent cement or less for adequate hardening. To identify these soils requires more testing. Since soil-cement is in the low-cost paving field, the testing engineer on large jobs should determine by test the minimum quantity of cement that can be safely used with each soil. By this procedure the lowest-cost soil-cement construction possible will be obtained.

Estimating Cement Requirements

The following information will aid the engineer in estimating cement requirements of the soils proposed for use and in determining what cement factors to investigate in the laboratory tests.

As a general rule, it will be found that the cement requirement of soils increases as the silt and clay content increases, gravelly and sandy soils requiring less cement for adequate hardness than silt and clay soils.

The one exception to this rule is that poorly graded, one-size sand materials that are devoid of silt and clay require more cement than do sandy soils containing some silt and clay.

In general, a well-graded mixture of stone fragments or gravel, coarse sand, and fine sand either with or without small amounts of feebly plastic silt and clay material will

*Since this material has been taken directly from the Portland Cement Association text, figure numbers and certain other references in this Appendix may not be in agreement with other portions of this report.

require 5 per cent or less cement by weight. Poorly graded one-size sand materials with a very small amount of nonplastic silt, typical of beach sand or desert blow sand, will require about 9 per cent cement by weight. The remaining sandy soils will generally require about 7 per cent. The nonplastic or moderately plastic silty soils generally require about 10 per cent cement by weight, and plastic clay soils require about 13 per cent or more.

Table 1 gives the usual range in cement requirements for subsurface soils of the various AASHO* soil groups. "A" horizon soils may contain organic or other material detrimental to cement reaction and may require higher cement factors. For most A horizon soils the cement content in Table 1 should be increased four percentage points if the soil is dark grey to grey and six percentage points if the soil is black. It is usually not necessary to increase the cement factor for a brown or red A horizon soil. Testing of "poorly reacting" sandy surface soils is discussed in detail in Chapter 8. These cement contents can be used as preliminary estimates, which are then verified or modified as additional test data become available.

Step-by-Step Procedure

The following procedure will prove helpful to the testing engineer in setting up cement contents to be investigated:

Step 1: Determine from Table 1 the preliminary estimated cement content by weight based on the AASHO soil group.

Step 2: Use the preliminary estimated cement content obtained in Step 1 to perform the moisture-density test.

Step 3: Verify the preliminary estimated cement content by referring to Table 2 if the soil is sandy or to Table 3 if it is silty or clayey. These tables take into consideration the maximum density and other properties of the soil, which permits a more accurate estimate. In the case of A horizon soils, the indicated cement factor should be increased as discussed above for Table 1.

Sandy soils:

(1) Using the percentage of material smaller than 0.05 mm., the percentage of material retained on the No. 4 sieve, and the maximum density obtained by test in Step 2, determine from Table 2 the estimated cement content.

(2) Mold wet-dry and freeze-thaw test specimens at the estimated cement content by weight obtained in (1) and at cement contents two percentage points above and below that cement factor.

Silty and clayey soils:

(1) Using the percentage of material between

*Charts and tables for use in classifying soils by the American Association of State Highway Officials Soil Classification System (AASHO Designation: M 145-49) are given in the appendix.

TABLE 1. Cement Requirements of AASHO Soil Groups

AASHO soil group	Usual range in cement requirement, per cent by vol.	Usual range in cement requirement, per cent by wt.	Estimated cement content and that used in moisture-density test, per cent by wt.	Cement contents for wet-dry and freeze-thaw tests, per cent by wt.
A-1-a	5- 7	3- 5	5	3- 5- 7
A-1-b	7- 9	5- 8	6	4- 6- 8
A-2	7-10	5- 9	7	5- 7- 9
A-3	8-12	7-11	9	7- 9-11
A-4	8-12	7-12	10	8-10-12
A-5	8-12	8-13	10	8-10-12
A-6	10-14	9-15	12	10-12-14
A-7	10-14	10-16	13	11-13-15

TABLE 2. Average Cement Requirements of B and C Horizon Sandy Soils

Material retained on No. 4 sieve, per cent	Material smaller than 0.05 mm., per cent	Cement content, per cent by wt. — Maximum density, lb. per cu.ft. 105–109	110–114	115–119	120–124	125–129	130 or more
0–14	0–19	10	9	8	7	6	5
	20–39	9	8	7	7	5	5
	40–50	11	10	9	8	6	5
15–29	0–19	10	9	8	6	5	5
	20–39	9	8	7	6	6	5
	40–50	12	10	9	8	7	6
30–45	0–19	10	8	7	6	5	5
	20–39	11	9	8	7	6	5
	40–50	12	11	10	9	8	6

TABLE 3. Average Cement Requirements of B and C Horizon Silty and Clayey Soils

AASHO group index	Material between 0.05 mm. and 0.005 mm., per cent	Cement content, per cent by wt. — Maximum density, lb. per cu.ft. 90–94	95–99	100–104	105–109	110–114	115–119	120 or more
0–3	0–19	12	11	10	8	8	7	7
	20–39	12	11	10	9	8	8	7
	40–59	13	12	11	9	9	8	8
	60 or more	—	—	—	—	—	—	—
4–7	0–19	13	12	11	9	8	7	7
	20–39	13	12	11	10	9	8	8
	40–59	14	13	12	10	10	9	8
	60 or more	15	14	12	11	10	9	9
8–11	0–19	14	13	11	10	9	8	8
	20–39	15	14	11	10	9	9	9
	40–59	16	14	12	11	10	10	9
	60 or more	17	15	13	11	10	10	10
12–15	0–19	15	14	13	12	11	9	9
	20–39	16	15	13	12	11	10	10
	40–59	17	16	14	12	12	11	10
	60 or more	18	16	14	13	12	11	11
16–20	0–19	17	16	14	13	12	11	10
	20–39	18	17	15	14	13	11	11
	40–59	19	18	15	14	14	12	12
	60 or more	20	19	16	15	14	13	12

0.05 mm. and 0.005 mm., the AASHO group index, and the maximum density obtained by test in Step 2, determine from Table 3 the estimated cement content.

(2) Mold wet-dry and freeze-thaw test specimens at the estimated cement content obtained in (1) and at cement contents two percentage points above and below that cement factor.

To help in determining how well the soil reacts, it is advantageous to save half of the last moisture-density test specimen and to place it in an atmosphere of high humidity for inspection daily. This half specimen, called the

Fig. 5. Soil-cement specimens saved from tail end of moisture-density test procedure. Rate of hardening of the soil-cement mixture is investigated from day to day with a dull-pointed instrument.

"tail-end" specimen (see Fig. 5), is obtained during the usual procedure of cutting the last specimen of the moisture-density test in half vertically (details are given on page 20) so that a representative moisture sample can be taken. The criteria used in the rapid test procedure, as discussed in Chapter 7, can be used to judge the hardness of the tail-end specimen. Generally, tail-end specimens are satisfactorily hardened in two to four days and it is not uncommon for them to be satisfactory a day after molding.

A study of compressive-strength data, as discussed in Chapter 4, is also helpful in checking the estimated cement factor

Miscellaneous Soils

A number of miscellaneous materials or special types of soils, such as caliche, chert, cinders, scoria, shale, etc., have been used successfully in soil-cement construction. In some cases these materials have been found in the roadway or street that was to be paved with soil-cement; in other cases, in order to reduce the cost of the project, they have been used as borrow materials to replace soils that required high cement contents for adequate hardening.

The procedure for testing miscellaneous materials is the same as that used for regular soils. Average cement requirements of a number of miscellaneous materials and cement contents to be investigated in the laboratory tests are given in Table 4. As test data are accumulated and experience is gained with local miscellaneous materials, it may be found that future testing can be reduced or eliminated for similar materials.

TABLE 4. Average Cement Requirements of Miscellaneous Materials

Type of miscellaneous material	Estimated cement content and that used in moisture-density test		Cement contents for wet-dry and freeze-thaw tests, per cent by wt.
	per cent by vol.	per cent by wt.	
Shell soils	8	7	5- 7- 9
Limestone screenings	7	5	3- 5- 7
Red dog	9	8	6- 8-10
Shale or disintegrated shale	11	10	8-10-12
Caliche	8	7	5- 7- 9
Cinders	8	8	6- 8-10
Chert	9	8	6- 8-10
Chat	8	7	5- 7- 9
Marl	11	11	9-11-13
Scoria containing material retained on the No. 4 sieve	12	11	9-11-13
Scoria not containing material retained on the No. 4 sieve	8	7	5- 7- 9
Air-cooled slag	9	7	5- 7- 9
Water-cooled slag	10	12	10-12-14

APPENDIX J

pH TEST TO DETERMINE LIME REQUIREMENTS FOR LIME STABILIZATION

pH TEST TO DETERMINE LIME REQUIREMENTS FOR LIME STABILIZATION

Materials:

1. Lime to be used for soil stabilization

Apparatus:

1. pH meter (the pH meter must be equipped with an electrode having a pH range of 14)
2. 150 ml. (or larger) plastic bottles with screw-top lids
3. 50 ml. plastic beakers
4. CO_2 - free distilled water
5. Balance
6. Oven
7. Moisture cans

Procedure:

1. Standardize the pH meter with a buffer solution having a pH of 12.45.
2. Weigh to the nearest 0.01 gms. representative samples of air-dried soil, passing the No. 40 sieve and equal to 20.0 gms. of oven-dried soil.
3. Pour the soil samples into 150 ml. plastic bottles with screw-top lids.

4. Add varying percentages of lime, weighed to the nearest 0.01 gm, to the soils. (Lime percentages of 0, 2, 3, 4, 5, 6, 8 and 10, based on the dry soil weight, may be used.)
5. Thoroughly mix soil and dry lime.
6. Add 100 ml. of CO_2 - free distilled water to the soil-lime mixtures.
7. Shake the soil-lime and water for a minimum of 30 seconds or until there is no evidence of dry material on the bottom of the bottle.
8. Shake the bottles for 30 seconds every 10 minutes.
9. After one hour, transfer part of the slurry to a plastic beaker and measure the pH.
10. Record the pH for each of the soil-lime mixtures. The lowest percent of lime giving a pH of 12.40 is the percent required to stabilize the soil. If the pH does not reach 12.40, the minimum lime content giving the highest pH is that required to stabilize the soil.

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